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This reissue replaces and supersedes the 17 April 1962 issue of this report.

Accession No. 01167-64

Copy No. 56 SID 62-203

APOLLO
RELIABILITY PROGRAM PLAN
(U)

NAS 9-150

Reissued 27 December 1963

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Prepared by

Apollo Reliability

AVAILABLE TO NASA HEADQUARTERS ONLY

Approved by

J. W. Paup
Vice President and Apollo Program Manager

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(NASA-CR-117256) APOLLO RELIABILITY PROGRAM PLAN (North American Aviation, Inc.) 304 p (CATEGORY)

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FOREWORD

This report provides an overall plan for implementation and administration of the Apollo reliability program in accordance with paragraph 3.8 of Exhibit I of the Definitive Contract NAS 9-150, Amendment 1 of military specification MIL-R-27542 (dated 31 October 1961), and NASA Quality Publication NPC 200-2 (dated 4 April 1962). The reliability program plan described herein presents the organization, controls, and procedures to be employed by North American Aviation in meeting the requirements specified in the listed documents.

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INTRODUCTION

Apollo reliability activities are designed to emphasize preventive rather than curative measures to achieve the extreme, man-rated reliability and safety objectives. To this end, the preventive elements of the program concentrate on high-integrity design, stringent control measures, comprehensive ground testing, and personnel selection, assignment, training, and motivation. The following curative measures will be employed to supplement the foregoing:

1. Corrective actions resulting from analyses and reviews of designs, processes, and controls.

2. Rapid-response failure and problem reporting which emphasizes corrective measures and evaluation of the effectiveness of such action.

3. Continuous program reviews and reorientation to establish new priorities and rapidly resolve current problems.

Each of these program elements is defined further in subsequent sections of this report.

This report is reviewed and periodically revised as required to reflect program orientation and content. It is in loose-leaf form to enable individual pages to be changed, as required, rather than necessitate revision of the entire report. Changes will be identified by revision bars placed in the margin where the revision occurs and revised pages will contain revision dates. Revised pages will be listed at the front of the volume. Where applicable, existing reports, procedures, and specifications are referenced in this document rather than being duplicated herein. Such detailed information is available through S&ID and will be supplied upon request.

This document defines the detailed requirements for the Apollo reliability program, within the scope of NAA contractual obligations. Deviations from applicable documents, previously referenced, are clearly delineated and will take precedence over the originally stated requirements. Numerical notations, in the form (1), in the outer margin of the applicable pages are references to deviations contained in Appendix I.

1. RELIABILITY POLICY AND ORGANIZATION

This section describes the S&ID reliability policy and organization, with emphasis placed on the applicability to the Apollo program. Organization charts are included to illustrate the functional relationships that exist between primary and supporting groups within the project.

RELIABILITY POLICY

Tightly integrated into Apollo development objectives and plans is the realization on the part of S&ID of the need for rapid and economical reliability growth and attainment of the maximum possible probabilities of success and crew survival. Management organizations and actions are directed toward this end. Resources and capabilities of the entire NAA corporate structure are available to assure program success.

The ambitious nature of the Apollo mission dictates that all management, functional, and support personnel recognize quality and reliability as parameters of equal or greater importance than cost, schedule, and performance. A centralized reliability program is fundamentally an aid to these individuals. It is not a substitute for dedication, thoughtfulness, care, and highly professional attitudes in performing assigned tasks, nor does it relieve any individual from his responsibilities toward ensuring that the spacecraft and support equipment are of high integrity, and, ultimately, that Apollo missions are successful.

MANAGEMENT AND ORGANIZATION

First-line responsibility for product integrity and quality rests with the division and Apollo program management. Apollo Reliability Engineering is delegated the responsibility for implementing a reliability program which will enhance achievement of reliability objectives. Reliability policy and guidance are provided by the Division President, Apollo Vice President and Program Manager, and Director of Test and Quality Assurance. (See Figure 1-1.)

Apollo Division

The Apollo Vice President and Program Manager is responsible to NASA and the Division President for the conduct of the program and for all

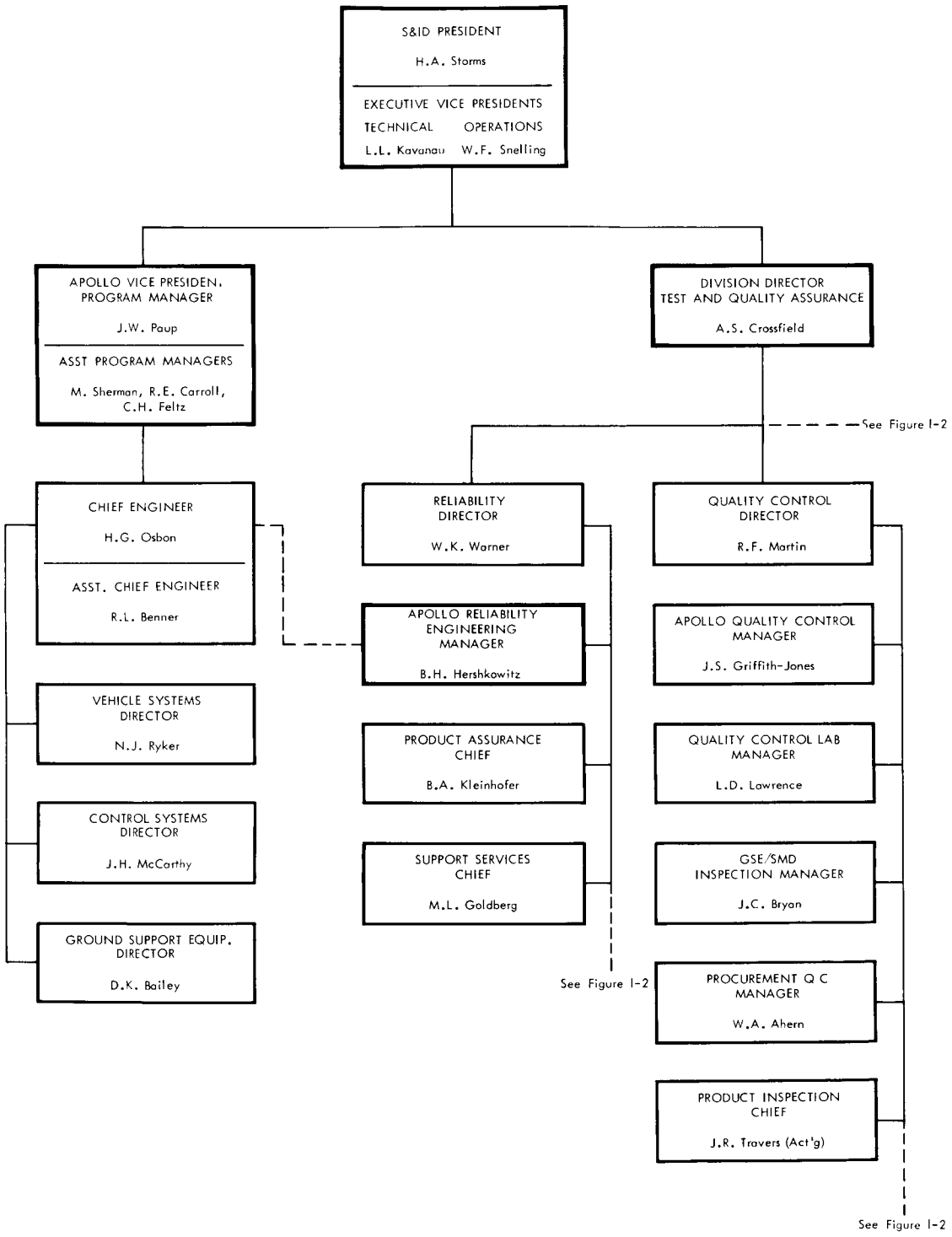


Figure 1-1. Apollo Reliability Organizational Responsibilities

its administrative and technical aspects. He is supported by a well-integrated organization representing the following functions:

Customer representatives
Associate contractor representatives
Program Control (S&ID, subcontractors, and suppliers)
Space Sciences
System Analysis
Subsystem Project Management
Material
Facilities
Logistics
Contracts
Engineering
Manufacturing
Administration
Test and Operations

Test and Quality Assurance

The Director of Test and Quality Assurance is responsible for the administration and conduct of S&ID reliability and quality. Within the framework of NASA and NAA corporate policies and requirements, he establishes Divisional reliability and quality policy and the organizations required to implement them. As illustrated in Figure 1-2, the Director of Test and Quality Assurance, and the organizations under him, advise, coordinate, and provide direct project support in the following fields:

Operations support
Data
Quality standards, engineering and control
Reliability analyses and reviews
Qualification tests
Statistics
Component application and evaluation
Training and certification

Apollo Reliability Manager

The Apollo Reliability Manager reports to the Director of Reliability Engineering and is in close technical contact with the Apollo Chief Engineer. The following are the responsibilities of the Reliability Manager:

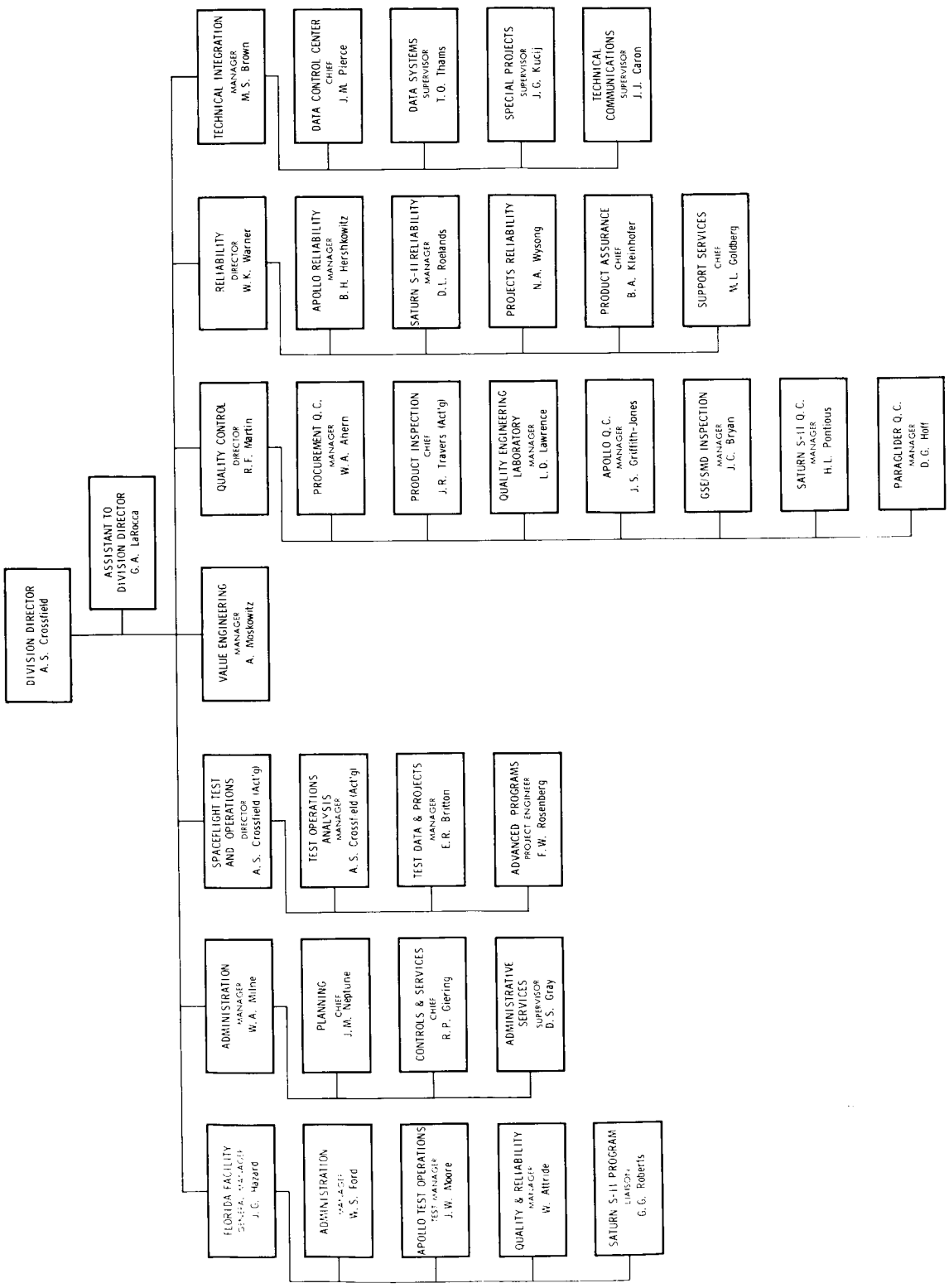


Figure 1-2. Test and Quality Assurance Organization

1. Foster and advance the concepts for achieving reliability and crew safety through preventive (rather than curative) measures. These include high-integrity design, stringent technical and administrative controls, comprehensive ground testing, and personnel selection, assignment, motivation, and training.

2. Define and implement the technical and administrative measures and controls, commensurate with NASA, corporate, and divisional policy and requirements.

3. Represent S&ID and Apollo program management in negotiations with NASA on specifications, work statements, deviations, and similar documents and on other matters having reliability and/or crew safety ramifications.

4. Guide and supervise the preparation of reliability program and test plans to assure compatibility with contractual obligations and NAA policy.

5. Assure that supplier work statements, procurement specifications, and documents generated by other NAA functional units contain suitable reliability and crew safety requirements.

6. Delineate the project and central reliability organizations and interrelationships required to implement the program and test plans.

7. Prepare work statements, manpower loads, skill requirements, and budget forecasts for all project and support reliability effort.

8. Maintain surveillance over all reliability activities, manpower employment, and expenditures to assure an adequate scope of effort and available skills and to preclude overruns.

9. Establish schedules for accomplishing, controlling, and auditing reliability activities.

10. Coordinate interdepartmental activities related to reliability and crew safety.

11. Conduct periodic, formal reliability program reviews.

12. Advise NASA, S&ID Apollo, Quality Assurance, and Engineering management on status and necessary reorientation to resolve problems and thereby enhance achievement of program requirements.

13. Ensure that contractual reliability documentation requirements are met on schedule.

14. Approve subcontractor and supplier reliability programs and all NAA and supplier documents containing reliability or crew safety information.

15. Ensure that reliability reports and recommendations are available to support design review activities.

16. Monitor and approve reliability motivational and training activities.

17. Approve all project reliability travel, overtime, procurement, and other expenditure authorizations.

Reliability Engineering

Apollo Reliability Engineering is the S&ID agency charged with the responsibility for delineating and implementing the reliability program and qualification test plans. Figure 1-3 shows the Apollo Reliability Engineering organization and supervisory personnel.

The functions and responsibilities of the Apollo Reliability Engineering organization are delineated in Figure 1-4. The organization consists of four units, which include analytical and test responsibilities, a design review function, and a criteria and evaluation unit. They are physically located in the project facility.

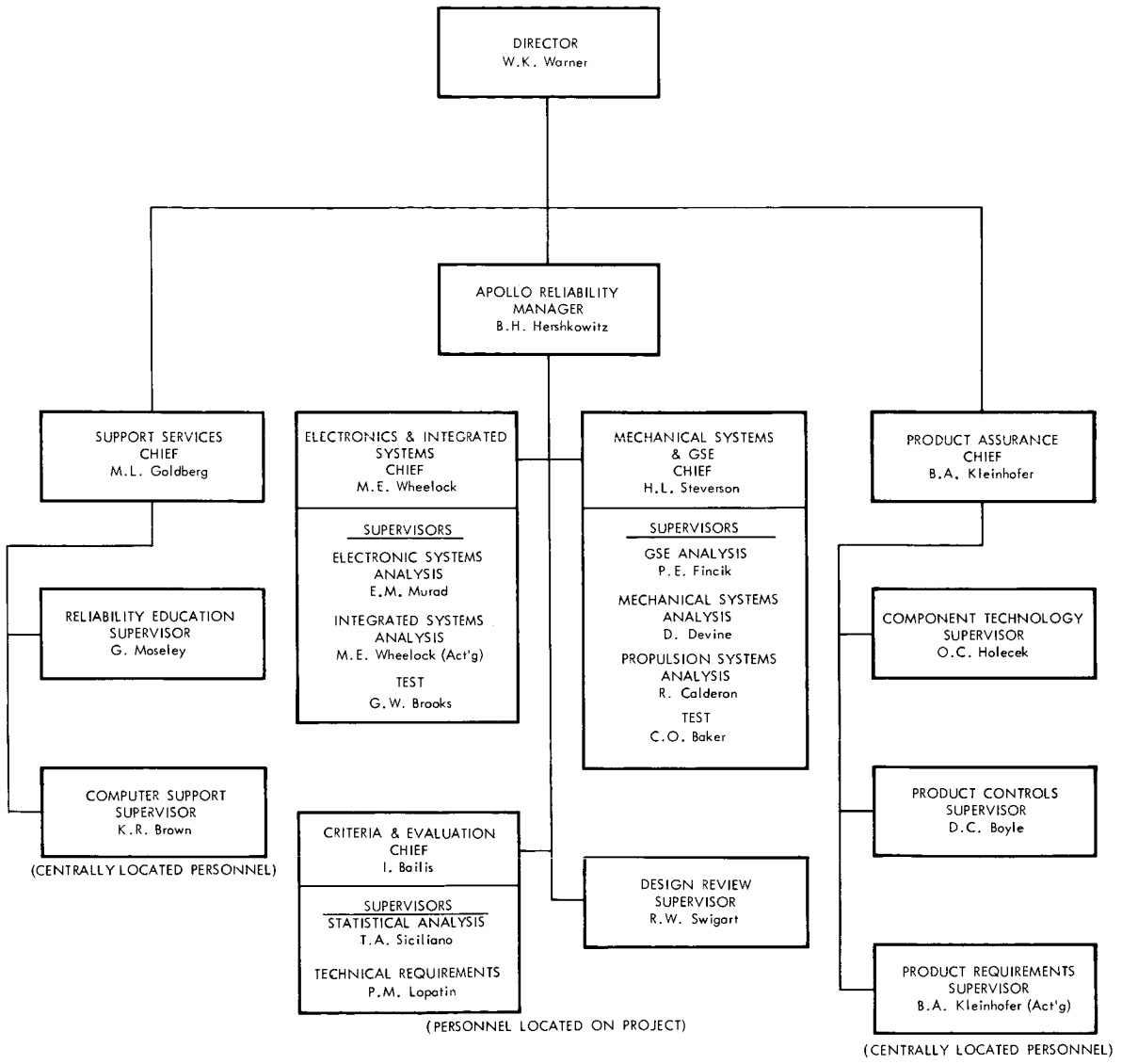


Figure 1-3. Reliability Engineering Organization

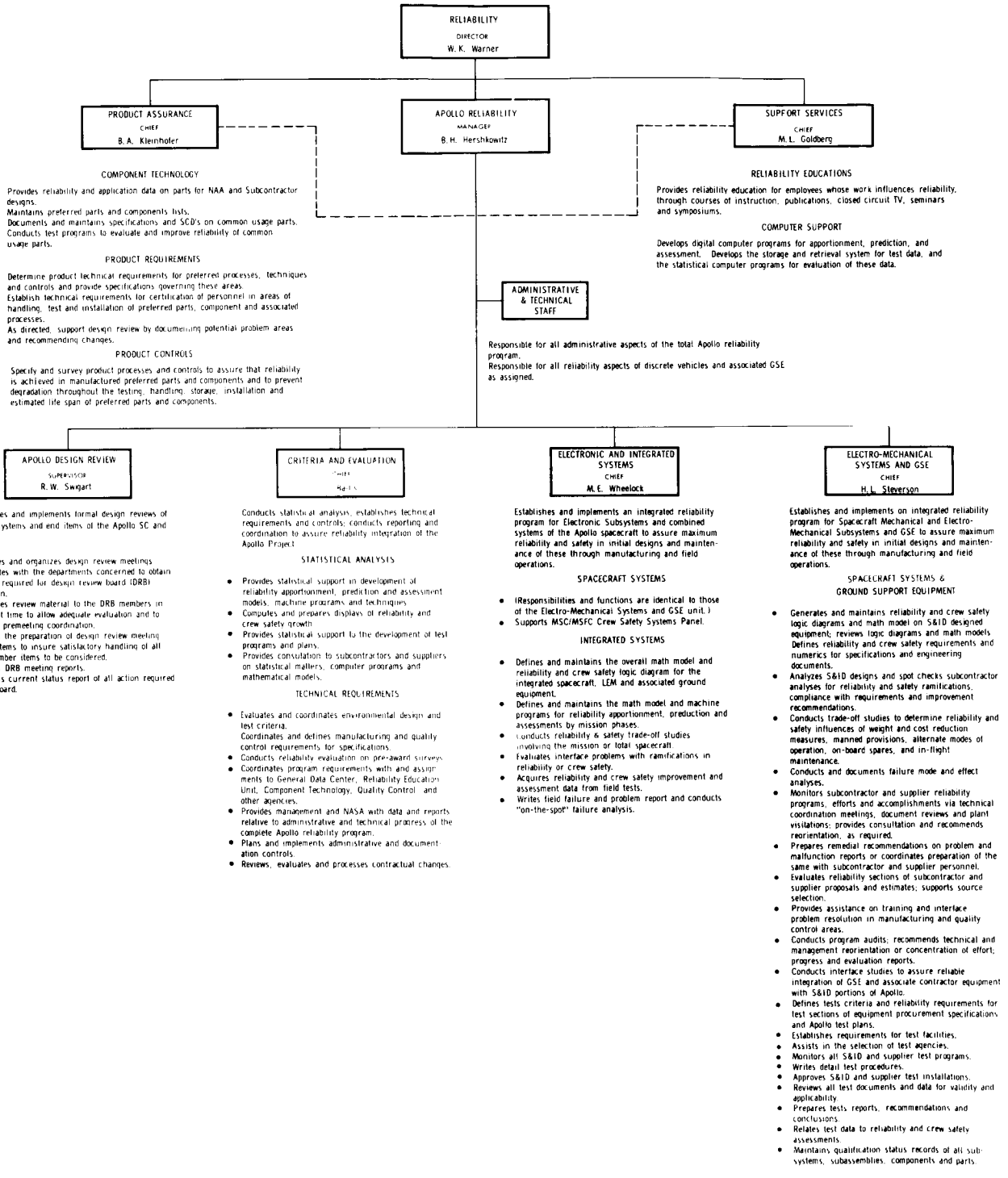

RELIABILITY
DIRECTOR
W. K. Warner
PRODUCT ASSURANCE
CHIEF
B. A. Kleinhofer
APOLLO RELIABILITY
MANAGER
B. H. Hershkowitz
SUPPORT SERVICES
CHIEF
M. L. Goldberg
COMPONENT TECHNOLOGY
Provides reliability and application data on parts for NAA and Subcontractor designs.
Maintains preferred parts and components lists.
Documents and maintains specifications and SCD's on common usage parts.
Conducts test programs to evaluate and improve reliability of common usage parts.
PRODUCT REQUIREMENTS
Determine product technical requirements for preferred processes, techniques and controls and provide specifications governing these areas.
Establish technical requirements for certification of personnel in areas of handling, test and installation of preferred parts, component and associated processes.
As directed, support design review by documenting potential problem areas and recommending changes.
PRODUCT CONTROLS
Specify and survey product processes and controls to assure that reliability is achieved in manufactured preferred parts and components and to prevent degradation throughout the testing, handling, storage, installation and estimated life span of preferred parts and components.
RELIABILITY EDUCATIONS
Provides reliability education for employees whose work influences reliability, through courses of instruction, publications, closed circuit TV, seminars and symposiums.
COMPUTER SUPPORT
Develops digital computer programs for apportionment, prediction, and assessment. Develops the storage and retrieval system for test data, and the statistical computer programs for evaluation of these data.
ADMINISTRATIVE & TECHNICAL STAFF
Responsible for all administrative aspects of the total Apollo reliability program.
Responsible for all reliability aspects of discrete vehicles and associated GSE as assigned.
APOLLO DESIGN REVIEW
SUPERVISOR
R. W. Swigart
Establishes and implements formal design reviews of the subsystems and end items of the Apollo SC and GSE.
• Schedules and organizes design review meetings coordinates with the departments concerned to obtain material required for design review board (DRB) evaluation.
• Distributes review material to the DRB members in sufficient time to allow adequate evaluation and to complete premeeting coordination.
• Monitors the preparation of design review meeting agenda items to insure satisfactory handling of all DRB member items to be considered.
• Prepares DRB meeting reports.
Maintains current status report of all action required by the board.
CRITERIA AND EVALUATION
CHIEF
Conducts statistical analysis, establishes technical requirements and controls; conducts reporting and coordination to assure reliability integration of the Apollo Project
STATISTICAL ANALYSIS
• Provides statistical support in development of reliability apportionment, prediction and assessment models, machine programs and techniques
• Computes and prepares displays of reliability and crew safety growth
• Provides statistical support to the development of test programs and plans.
• Provides consultation to subcontractors and suppliers on statistical matters, computer programs and mathematical models.
TECHNICAL REQUIREMENTS
• Evaluates and coordinates environmental design and test criteria.
Coordinates and defines manufacturing and quality control requirements for specifications.
• Conducts reliability evaluation on pre-award surveys
• Coordinates program requirements with and assignments to General Data Center, Reliability Education Unit, Component Technology, Quality Control and other agencies.
• Provides management and NASA with data and reports relative to administrative and technical progress of the complete Apollo reliability program.
• Plans and implements administrative and documentation controls.
• Reviews, evaluates and processes contractual changes.
ELECTRONIC AND INTEGRATED SYSTEMS
CHIEF
M. E. Wheelock
Establishes and implements an integrated reliability program for Electronic Subsystems and combined systems of the Apollo spacecraft to assure maximum reliability and safety in initial designs and maintenance of these through manufacturing and field operations.
SPACECRAFT SYSTEMS
• (Responsibilities and functions are identical to those of the Electro-Mechanical Systems and GSE unit.)
• Supports MSC/MSFC Crew Safety Systems Panel.
INTEGRATED SYSTEMS
• Defines and maintains the overall math model and reliability and crew safety logic diagram for the integrated spacecraft, LEM and associated ground equipment.
• Defines and maintains the math model and machine programs for reliability apportionment, prediction and assessments by mission phases.
• Conducts reliability & safety trade-off studies involving the mission or total spacecraft.
• Evaluates interface problems with ramifications in reliability or crew safety.
• Acquires reliability and crew safety improvement and assessment data from field tests.
• Writes field failure and problem report and conducts "on-the-spot" failure analysis.
ELECTRO-MECHANICAL SYSTEMS AND GSE
CHIEF
H. L. Steverson
Establishes and implements on integrated reliability program for Spacecraft Mechanical and Electro-Mechanical Subsystems and GSE to assure maximum reliability and safety in initial designs and maintenance of these through manufacturing and field operations.
SPACECRAFT SYSTEMS & GROUND SUPPORT EQUIPMENT
• Generates and maintains reliability and crew safety logic diagrams and math model on S&ID designed equipment; reviews logic diagrams and math models Defines reliability and crew safety requirements and numerics for specifications and engineering documents.
• Analyzes S&ID designs and spot checks subcontractor analyses for reliability and safety ramifications, compliance with requirements and improvement recommendations.
• Conducts trade-off studies to determine reliability and safety influences of weight and cost reduction measures, manned provisions, alternate modes of operation, on-board spares, and in-flight maintenance.
• Conducts and documents failure mode and effect analyses.
• Monitors subcontractor and supplier reliability programs, efforts and accomplishments via technical coordination meetings, document reviews and plant visitations; provides consultation and recommends reorientation, as required.
• Prepares remedial recommendations on problem and malfunction reports or coordinates preparation of the same with subcontractor and supplier personnel.
• Evaluates reliability sections of subcontractor and supplier proposals and estimates; supports source selection.
• Provides assistance on training and interface problem resolution in manufacturing and quality control areas.
• Conducts program audits; recommends technical and management reorientation or concentration of effort; progress and evaluation reports.
• Conducts interface studies to assure reliable integration of GSE and associate contractor equipment with S&ID portions of Apollo.
• Defines tests criteria and reliability requirements for test sections of equipment procurement specifications and Apollo test plans.
• Establishes requirements for test facilities.
• Assists in the selection of test agencies.
• Monitors all S&ID and supplier test programs.
• Writes detail test procedures.
• Approves S&ID and supplier test installations.
• Reviews all test documents and data for validity and applicability.
• Prepares tests reports, recommendations and conclusions.
• Relates test data to reliability and crew safety assessments.
• Maintains qualification status records of all subsystems, subassemblies, components and parts.

Figure 1-4. Apollo Reliability Organizational Responsibilities

Central Reliability Functions

Product assurance and Support Services provide centrally located support functions for Apollo Reliability, with specialists in the following specific areas. Component-Technology provides support by evaluating and maintaining reliability data and specifications on preferred and common usage parts. Product Requirements aids in determining and documenting preferred manufacturing processes and methods to be used in the assembly of parts and components. Product Controls provides support in the continuous surveillance of part and component manufacturers as well as installation, handling, packaging, identification and traceability processes for preferred and common usage parts and components. Reliability Education provides educational and motivational material for those employees whose work influences reliability. Computer Support develops Apollo Reliability computer programs, including data storage and retrieval systems.

Other Support Functions

Test and Quality Assurance organizations that provide support to Apollo Reliability are Apollo Data Control and Value Engineering. Apollo Data Control provides a central data function which develops systems to maintain, process, and report data originating in Apollo Reliability. Value Engineering provides support in cost reduction and value analysis associated with Apollo design reliability.

RELIABILITY MILESTONES AND STATUS

Figures 1-5, 1-6, and 1-7 show the status of completed and scheduled reliability milestones. The milestones are periodically updated and submitted per contract agreement.

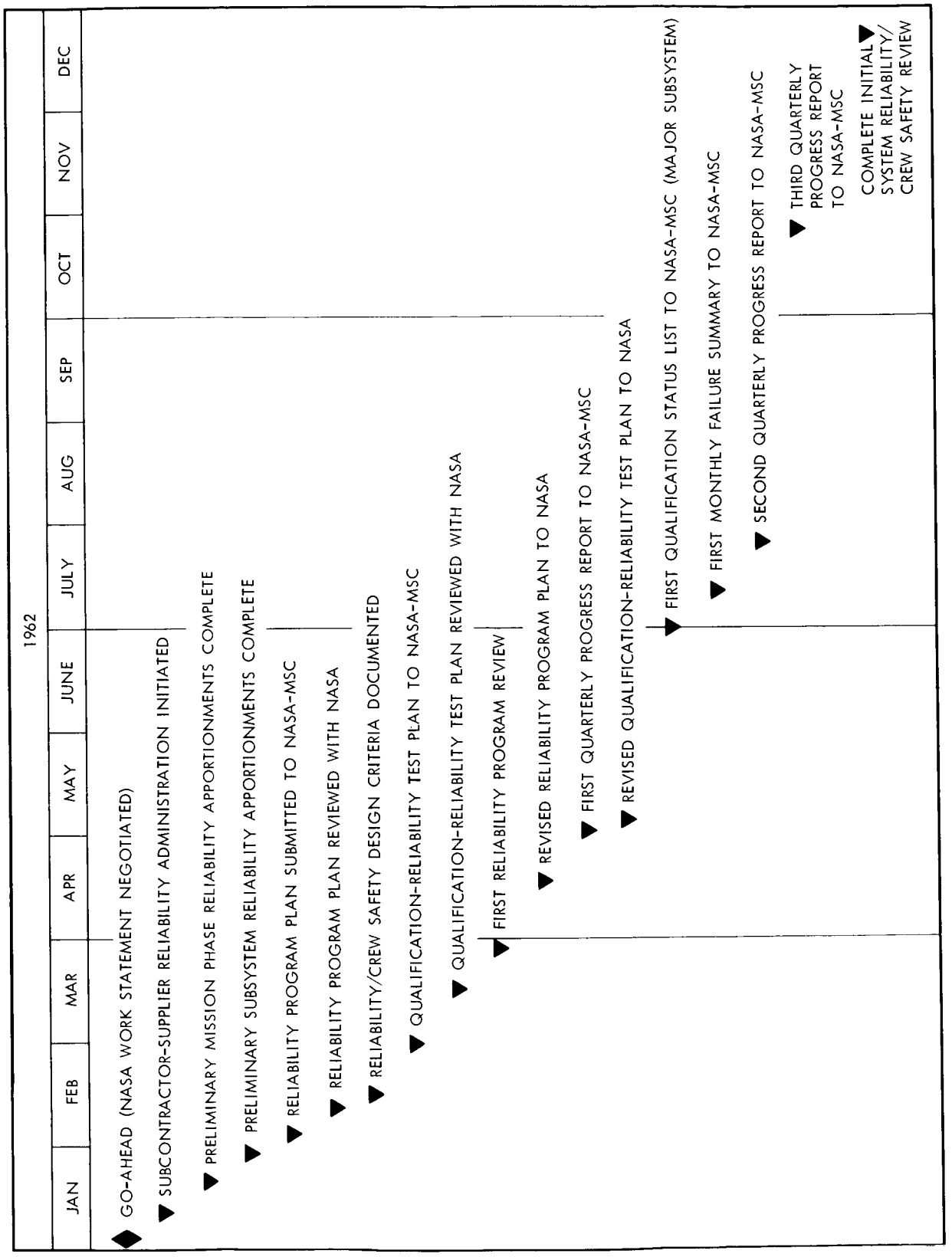


Figure 1-5. Reliability Milestones and Status, 1962

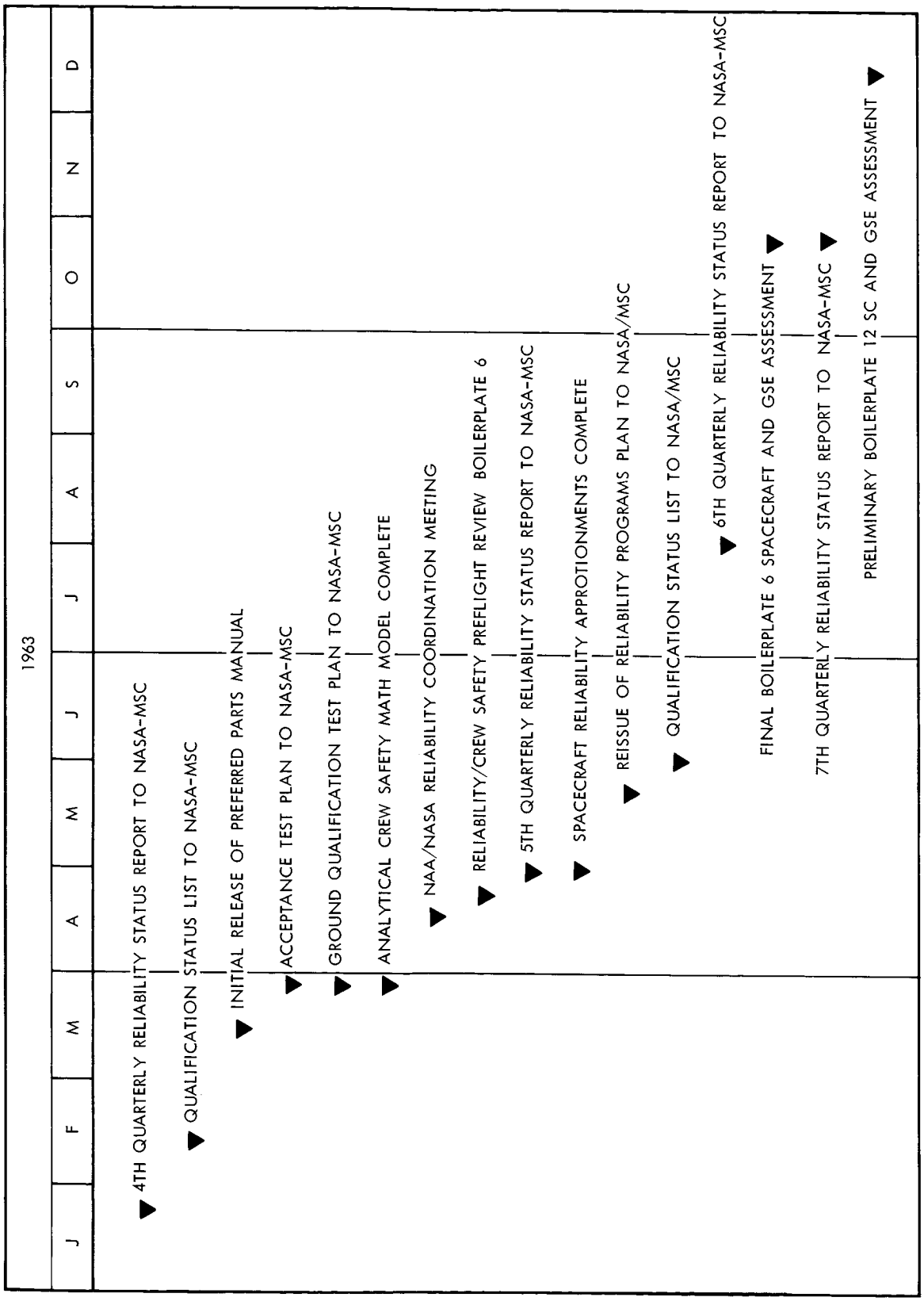
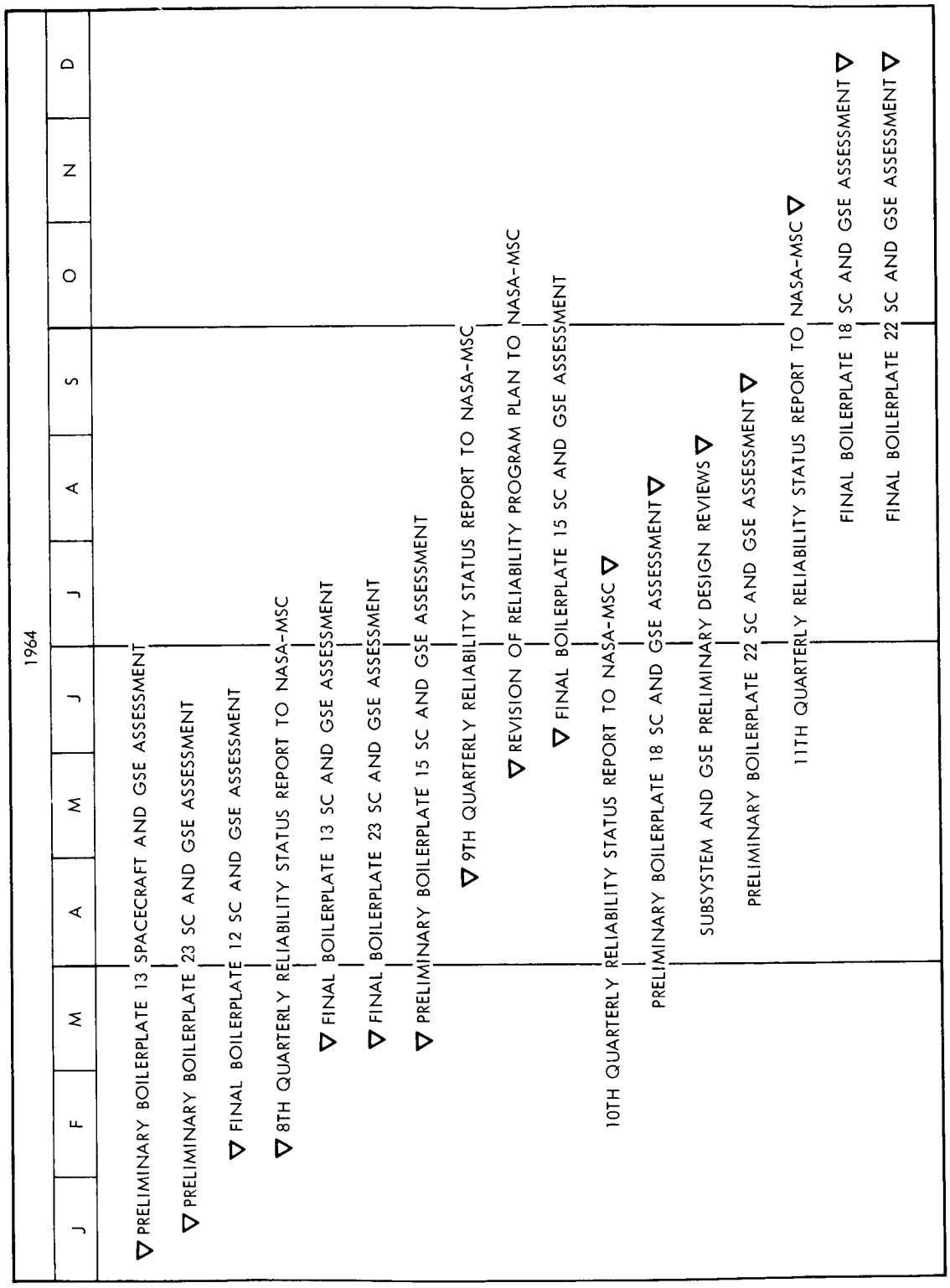


Figure 1-6. Reliability Milestones and Status, 1963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PRELIMINARY BOILERPLATE 13 SPACECRAFT AND GSE ASSESSMENT
PRELIMINARY BOILERPLATE 23 SC AND GSE ASSESSMENT
FINAL BOILERPLATE 12 SC AND GSE ASSESSMENT
8TH QUARTERLY RELIABILITY STATUS REPORT TO NASA-MSC
FINAL BOILERPLATE 13 SC AND GSE ASSESSMENT
FINAL BOILERPLATE 23 SC AND GSE ASSESSMENT
PRELIMINARY BOILERPLATE 15 SC AND GSE ASSESSMENT
9TH QUARTERLY RELIABILITY STATUS REPORT TO NASA-MSC
REVISION OF RELIABILITY PROGRAM PLAN TO NASA-MSC
FINAL BOILERPLATE 15 SC AND GSE ASSESSMENT
10TH QUARTERLY RELIABILITY STATUS REPORT TO NASA-MSC
PRELIMINARY BOILERPLATE 18 SC AND GSE ASSESSMENT
SUBSYSTEM AND GSE PRELIMINARY DESIGN REVIEWS
PRELIMINARY BOILERPLATE 22 SC AND GSE ASSESSMENT
11TH QUARTERLY RELIABILITY STATUS REPORT TO NASA-MSC
FINAL BOILERPLATE 18 SC AND GSE ASSESSMENT
FINAL BOILERPLATE 22 SC AND GSE ASSESSMENT

Figure 1-7. Reliability Milestones and Status, 1964

II. RELIABILITY/CREW SAFETY REQUIREMENTS AND APPORTIONMENT

REQUIREMENTS

As a goal, and in accordance with paragraph 2. 1. 3. 1, Exhibit B, Technical Specification, of the Definitive Contract NAS9-150, the probability of accomplishing the Apollo mission objectives will be 0. 90. Mission objectives are based upon a lunar landing of the lunar excursion module and earth return of the command module, including successful recovery of the crew upon earth landing.

In addition, the probability specified in paragraph 2. 1. 3. 2. 1 of the definitive contract will be 0. 90 that the crew will not have been subjected to conditions greater than the nominal limits given in the crew safety requirements section of Exhibit B, the probability specified in paragraph 2. 1. 3. 2. 2 will be 0. 999 that the crew will not have been subjected to conditions greater than the emergency limits given. The design criteria for nominal and emergency limits are specified in paragraphs 2. 4. 1 and 2. 4. 2, Exhibit B, Technical Specification, Part 3, of the Apollo Spacecraft Definitive Contract NAS9-150.

APPORTIONMENT

Reliabilities of the ground complex, launch vehicle, navigation and guidance system, and Apollo command, service, and lunar excursion modules affect the probability of successful accomplishment of the Apollo mission objectives, as delineated in Table 2-1. In order to define requirements for the command and service modules, a reliability objective of 0. 90 was apportioned to each of the major elements.

RELIABILITY DEFINITIONS

The following definitions, which have been derived from mission requirements, realistically define the expected mission success and crew safety objectives.

Mission Success. The mission will be considered successful if the following functions are accomplished.

1. The spacecraft successfully reaches the moon and enters lunar orbit.

2. The LEM lands on the moon; limited exploration is accomplished.

CONFIDENTIAL

Table 2-1. Apollo/Saturn System Reliability Apportionments

System	Mission Success	Crew Safety
GSE	0.9999	0.99999
GOSS	0.999	0.99999
Boosters (defined by NASA)	0.950	*
Command and service modules (including guidance and navigation equipment)	0.9638	0.99952
LEM (defined by NASA)	0.984	0.9995
Apollo/Saturn	0.90	0.999

*Since crew safety apportionments for the boosters have not been defined, it was assumed that all booster failures were of the type that would provide the opportunity of aborting with either the launch escape system or the command/service module complex.

3. The LEM and command module and service module rendezvous, and the personnel are transferred to the command module.

4. The command module returns to earth and lands without exposing the personnel to environments exceeding the emergency limits.

5. The command module is capable of sustaining the crew for one day inside the crew compartment and six days in the vicinity of the impact point.

Crew Safety. Crew safety probability is the sum of mission success reliability and the probability of having to abort and accomplishing the abort safely. Safe abort consists of the command module returning to earth prior to the scheduled time and landing safely without the crew being exposed to environments that exceed the emergency limits. Furthermore, the command module must be capable of sustaining the crew for one day inside the crew compartment and six days in the vicinity of the point of impact.

Abort Criterion. For design purposes, it is assumed that the mission will be aborted if sufficient failures occur in operating systems or equipment so that one additional failure would eliminate the capa-

bility of safe abort. This criterion does not apply to nonoperating systems, such as structure. It may be modified in individual cases if it indicates an unacceptable trade-off between mission success and crew safety.

The probability of mission success encompasses not only equipment reliability, but also operational procedures. The crew safety definition considers that the crew will be recovered if (1) the mission is successfully completed or (2) the mission is aborted prior to successful completion and a successful abort is accomplished without the crew being exposed to environments that exceed the emergency limits.

SUBSYSTEM APPORTIONMENTS

Subsystem reliability requirements have been established and are being implemented. They are as follows:

1. A requirement for successful completion of the mission through minimum lunar exploration with no failures that would cause a mission abort and successful return to the earth with no failures that would preclude safe recovery of the crew.

2. A requirement that a safe abort can be achieved with a specified probability.

The preliminary requirements for subsystem mission success are contained in Table 2-2.

The first requirement is based on the defined abort criterion and is augmented by a specified probability requiring an abort if certain equipment within a particular subsystem fails. This results from the fact that this equipment will be backed up by redundant pieces of equipment within a second subsystem and, hence, abort will be required only if the redundant equipment within the second subsystem fails. An example of this is shown in Figure 2-1.

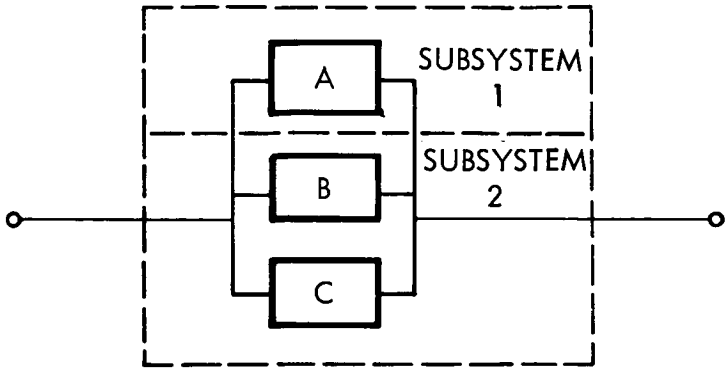


Figure 2-1. Intersubsystem Logic Diagram

[redacted]

Table 2-2. Apollo Command Module/Service Module Subsystem Apportionments

Subsystem	LOR Reliability Apportionments	
	Mission Success	Crew Safety
Structural and mechanical	0.999945	0.999945
Launch escape*	0.999989	0.999940
Electrical power	0.998600	0.999970
Earth landing	0.999940	0.999940
Cryogenic storage	0.999600	0.999999
Service module reaction control	0.999400	0.999980
Command module reaction control	0.999950	0.999960
Environmental control	0.990000	0.999912
Service propulsion	0.999200	0.999970
Stabilization and control	0.992600	0.999990
Guidance and navigation	0.985000	0.999967
Communications and data	0.999000	0.999998
Instrumentation	0.999990	0.999999
Overall Command Module and Service Module	0.963800	0.999520

*Indicates successful tower jettison

The function shown in Figure 2-1 can be accomplished in three ways, utilizing equipment A, B, or C. When subsystem 1 is evaluated alone, both a mission abort and a crew loss would be indicated with a failure of A, since it is the only equipment available for this function. However, because two equipments are available for backup in subsystem 2, no abort would be necessary if A failed. It, therefore, is necessary to specify to the subcontractor of subsystem 1 the probability of B or C failing, since an abort would be required only under this condition.

For that part of the mission following LEM lift-off, safe return to earth utilizing any equipment is considered satisfactory for mission success. Backup modes of equipment from other subsystems are to be considered.

The second requirement replaces the crew safety probabilities previously used. This change is necessary because of the basic definition of crew safety, which includes a successful mission, as well as safe abort. Since abort is instigated due to failures in any subsystem, the subsystem cannot be evaluated independently. When the requirement for determining the probability of safe abort is being considered, the probability of an abort actually taking place must also be recognized, whether the abort is due to failures within the subsystem under consideration or due to failures in other subsystems. In addition, the expected time during the mission when an abort would occur must be specified, and the possible reasons for such an abort occurring must be determined by the subcontractor. When the probability of safe abort is being calculated, the subcontractor must consider the probability of subsystems, other than his own, causing abort during which either all of his equipments are operable or certain equipments within his subsystem have failed.

GROUND SUPPORT EQUIPMENT

Program, General

As a means of attaining the high degree of probability of mission success apportioned to the ground support equipment, a standard ground rule has been applied to all equipment to categorize it according to usage. The ground rule is that equipment that is used in the final checkout and countdown portion of the prelaunch operation and affects the mission success or crew safety is assigned to a mission essential equipment category. A full reliability program has been imposed upon this equipment.

The basic criterion for GSE is the probability that the GSE will not cause the command module and service module reliability to fall below its requirement of 0.9638 and the GSE reliability will be at least 0.9999. The crew safety requirements are 0.99958 for the command module and service module and 0.99999 for GSE. This is interpreted to mean that the probability of the GSE, while in operation, creating or inducing an undetectable catastrophic failure in the spacecraft equipment will be 0.0001 or less.

The following factors will be considered when detailed equipment failure effects analyses are performed.

1. Probability of inducing failures in the spacecraft that are subsequently either detectable or undetectable.

2. Probability of GSE failures occurring that will result in subsequent spacecraft failures that will not be detected

3. Probability of accepting defective spacecraft equipment

4. Probability of rejecting good spacecraft equipment

A major consideration in the attainment of the degree of reliability apportioned to detailed ground support equipment is a prelaunch operational readiness program which will be implemented when NASA approves Master Development Schedule #7. The prelaunch operations analysis program will supply a tool for establishing spacecraft and GSE design parameter requirements necessary to allow the operational readiness requirement to be met. Operational readiness is defined as the average percent of Apollo spacecrafts that are successfully launched within the the required time envelope. In addition, the program would provide a capability for quantitative evaluation of predicted operational readiness and operating cost for any particular set of design parameters, such as reliability of GSE, time of maintenance tasks, level of the smallest replaceable unit (GSE or spacecraft), number of spares available, recycle or pipeline time for failed items, and amount of maintenance manpower and equipment.

Classification

The five general types of ground support equipment (i.e., auxiliary, checkout, handling, servicing, and training) are subdivided into three categories, depending on their intended usage. The categories are defined as follows:

1. Mission Essential Equipment (MEE). Those subsystems that are directly involved in a closed-loop operation with the spacecraft system or a spacecraft subsystem and have a function that may affect mission success or crew survival

2. Operating Ground Equipment (OGE). That equipment used in the support of mission essential equipment, spacecraft subsystems, checkout areas, staging areas, manufacturing facilities, etc.

3. Support Ground Equipment (SGE). The equipment and facilities utilized in transport, handling, maintenance, recovery, shelter, etc.

Only mission essential equipment contributes to crew safety and mission success probabilities, and it is apportioned accordingly. The important thing is that the work statement requirements for GSE reliability

be concerned with the modes of GSE failures that have an adverse effect on spacecraft equipments and the frequency of occurrence of these types of failures. The mean time between failures, either catastrophic or nuisance, would affect the operational readiness of the Apollo, and a recycle of the countdown, either partial or total, would be necessary.

Subsystem Assessment and Analysis Program

Each mission essential GSE end item is assessed on the basis of the following reliability requirements: (1) allowable frequency of failures that affect inherent mission success probability, (2) allowable frequency of failures that affect spacecraft inherent crew safety probability, and (3) MTBF's (including nuisance, as well as catastrophic failures). MTBF requirements are established for OGE and SGE. The purpose of this effort is to minimize, consistent with program objectives, the frequency of unavailability of these types of equipment.

The analytical methods employed in determining GSE reliability on mission essential equipment (MEE) are compatible with requirements as defined in Section III, Analysis Techniques, and Section IV, Apollo Design Review. The analysis function include worst-case, failure modes and effects, and failure probability analyses. The results of these reliability assessments for each piece of MEE will be published in a future Apollo Quarterly Reliability Status Report.

III. DESIGN RELIABILITY

One of the primary objectives of the Apollo development program is to enhance achievement of the reliability and crew safety goals prior to the first manned flight. To attain this objective, every available reliability design technique must be used. Some of the high-integrity techniques that will be employed are adequate design margins, system simplification, fail-safe provisions, redundancy, in-flight maintenance, and the use of the crew in primary and redundant system functions. The methods utilized are discussed in the following paragraphs, along with the analysis techniques for assuring adequate design.

Early in the Apollo design stage, an investigation will be made to determine the mechanization of each subsystem that will be used to meet the objectives. In arriving at proper mechanization, extensive trade-off studies will be made of the requirements in performance, weight, volume, reliability, and cost. The mechanization decisions that will be established for Apollo will be presented in the design criteria specification (report SID 62-65.

PREFERRED PARTS

Standard Parts Manual

The Reliability Parts Manual, Preferred Parts, has been incorporated into the S&ID Standard Parts Manual. The reliability parts section of this manual has been arranged to control parts used in the system by means of optimum part selection, correct part design application, controlled part procurement, appropriate part handling methods, including packaging, transportation, storage, identification and traceability, necessary part processing and installation controls, and total past history and data surveillance.

Each S&ID preferred part listed in the Reliability section of the Standard Parts Manual is available in two quality levels: S&ID high reliability, and general usage. Procurement specifications control each part level and are invoked by control numbers listed on the first page of the application data sheets for each part. The two quality levels are physically and functionally equivalent. The S&ID high-reliability level parts are used in design areas where reliability is a critical consideration, whereas non-critical applications utilize the general usage level parts.

Electronic Parts

The efforts of previous space projects, in addition to the Apollo program to reduce the failure rate of electronic parts, have resulted in parts with a reliability one to two orders of magnitude greater than previously available. This increase in the reliability of parts has been the result of complete documentation in manufacturing and quality control procedures and the determination and minimization of all possible failure modes for each device. As new failure modes are encountered, the materials, processes, or environments that induce the failure mode are reviewed, revised, and documented to preclude recurrence. Statistically designed experiments and accelerated tests are extensively employed to expose various failure modes and evaluate the effectiveness of the corrective actions.

The techniques employed become part of the procurement specification, so that all suppliers will continuously improve the parts being used in the system. Procurement specifications employ tests on either a lot or daily sampling basis to ensure that the parts produced by each supplier meet minimum requirements for environmental, accelerated-life, and usage conditions. The part failure rate under application or accelerated conditions is verified at a 60-percent confidence limit at various intervals throughout the program.

Parameter Stability Data

The failure of a part can be attributed either to a catastrophic failure caused by a short or open condition of one of the major elements of the device or to a change in one or more of the operating parameters beyond prescribed limits. The catastrophic failure mode can be eliminated only by the manufacturer through rigid process and quality control methods during the manufacturing cycle, coupled with a complete knowledge of the various steps of the process where an incipient catastrophic failure mode can be introduced into the product. Drift can generally be compensated for by the circuit designer's ensuring that the maximum drift will not cause a circuit or system failure.

An extensive program has been implemented to determine and optimize the stability and/or variance of important parameters under various combinations of electrical and temperature stresses. This program yields information on the statistical distribution of variables as a

function of time that is made available to design engineers and is employed in the analysis of various circuits during the preliminary design period. Combined supplier and consumer data are used to evaluate the effect of electrical and environmental stresses, for short or long periods of time, on the failure rate at specified parameter limits.

Use of Minuteman Parts

Considerable background in parts reliability improvement techniques has been gained from the Minuteman program. However, before any Minuteman part will be accepted for Apollo use, it will be determined that the known failure rate and environmental capabilities of the part are compatible with Apollo requirements. In lieu of repetitive tests, the maximum available data will be screened for application suitability on Apollo.

Electromechanical Parts

The reduction of failures of electromechanical parts having an apportioned failure rate consistent with Apollo requirements will require a diligent program, vigorously pursued, through the entire life of the equipment.

Expected Failure Modes

The expected failure modes of electromechanical parts include surface wear, fatigue, corrosion, degradation with time, and lubricant failures, most of which are amenable to analytical methods of evaluation and resolution. However, little is known concerning the quantitative effects of minute variations and imperfections on the mechanics of failure. This lack of data develops a multitude of indeterminates. For this reason, the application and usage of electromechanical parts for the Apollo program must involve critical attention to the smallest details to minimize the influence of these indeterminates.

In some instances, parts must be designed for the specific application at the sacrifice of the economics of standardization. In other cases, part improvement effort may be required to advance the state of the art so that desired reliability goals can be approached. A noncompromising philosophy of raw material control that will preclude the use of faulty material will be developed. Extremely rigorous in-process controls will be implemented to obtain the ultimate in fabrication techniques, dimensional control, surface finish requirements, manufacturing processes, and other criteria necessary to yield a consistent part having an absolute minimum of minute variations.

ANALYSIS TECHNIQUES

Estimates of Design Reliability

Equipment Reliability

The reliability of equipment is dependent upon the environment and operational conditions to which the equipment is subjected. A preliminary estimate of these conditions will be made by design and reliability engineers, based on classical techniques.

It is assumed that the equipment has been started and is operating, that no unfavorable transients are experienced during the starting operation, that the parts are free of "infant mortality" or wearout, and that the failure rate is constant. The reliability of the parts is assumed to be the exponential with respect to time as given by the estimator,

$$R = e^{-\lambda t}$$

where

λ = Failure rate

t = Operating time

This assumes that all parts are connected in series and that a failure of any one part will result in loss of function within the subject equipment. Under these assumptions there is justification to permit multiplying the probability of success P_S values or adding the failure rate values for each part. A typical example employing this reliability prediction technique is given in Figure 3-1.

If the equipment is started while in flight or is subjected to on-off cyclic operations, then the reliability is the product of probabilities of starting and operating, or

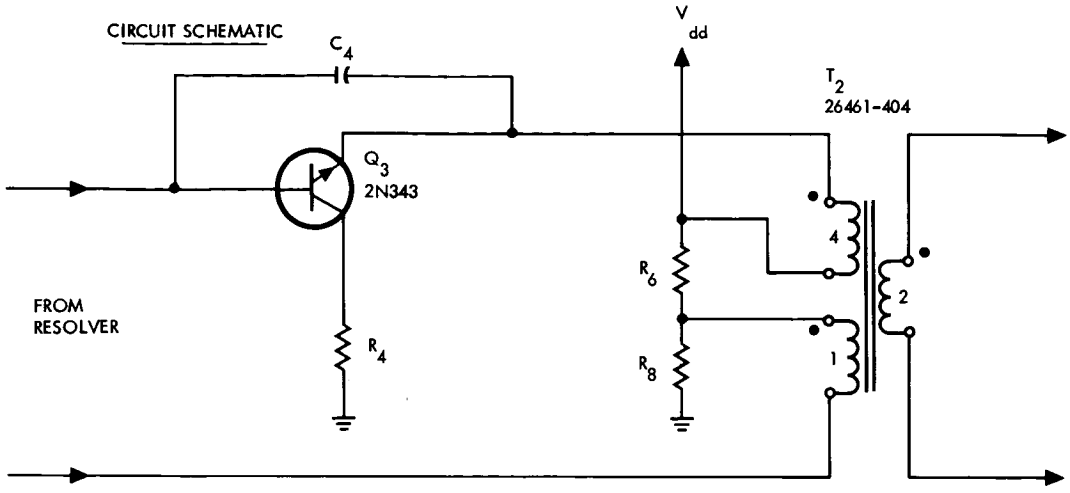
$$R = e^{-nr} (e^{-\lambda t})$$

where

n = Number of required starts

r = Ratio of unsuccessful starts to start attempts

CIRCUIT SCHEMATIC



PART USAGE

Part Identification	Recommended Maximum Rating	Actual Application Rating	Failure Rate (Percent Per 1000 Hr)
Transistor Q3 2N343 I_c	50 ma	2 ma	
V_c	30 v	28 v	
P_c	250 mw	56 mw	
θ	0.125 C/mw	0.15C/mw	
T_j	55C	48.4 C	0.0008
Capacitor C_4 (220 $\mu\mu$f Glass)	300 v	27 v	0.00005
Resistor R_4 (100 carbon)	0.125 w	0.004 w	0.00008
Resistor R_6 (15 k Carbon)	0.125 w	0.0382 w	0.00008
Resistor R_8 (510 Carbon)	0.125 w	0.0013 w	0.00008
Audio Transformer T_2 (7 Terminals)			0.0030
			0.00409

Note: Assume 14-day (336-hour) operating time

$P_s = e^{-\lambda t} = 0.999986$

Figure 3-1. Example of Operating Failure Rate Prediction

Failure rates thus determined will be compared to the failure rates apportioned from mission objectives to ascertain if the objectives have been met. If the objectives have not been met, then part redundancy, circuit redundancy, simplification of design, derating, and changes in operating conditions will be some of the means that may be used to solve the problem.

System Reliability

Reliability analytical models will be derived for the Apollo system. These models will take into consideration any modes of operation inherent in the equipment that will allow the use of one equipment or group of equipment to perform a secondary function in the absence of the ability to perform the function by normal means. These models will be utilized to assess the system's ability to meet the reliability objectives, as well as to determine methods to achieve the reliability objectives. These models will also be utilized in trade-off studies conducted at the required level.

Environmental Analyses

In addition to the failure rate prediction methods, analytical techniques are available to assist in developing equipment that will be free from adverse environmental influences and to ensure that no reliability degradation will occur. These include thermal, vibration, and shock analyses.

Use of Derating Factors

Derating factors or design margins will be used extensively in the Apollo design. Sufficiently large design margins will be incorporated to assure that the probability of failure due to overstress of the product is kept to a minimum. Figure 3-2 is a simplified illustration of the design margin concept.

To apply this concept, distributions of applied and limit loads or stresses will be determined. The distribution of strength is caused by variations in workmanship, material, and processes. The distribution of applied load is caused by self-induced stresses and variations in environmental conditions.

Sufficient knowledge is available to apply this technique, on a limited basis, early in the design. A continuous effort will be made to expand this information through supplier surveys and part evaluation tests. The design margin approach to reliability employs terminology that the designer uses constantly.

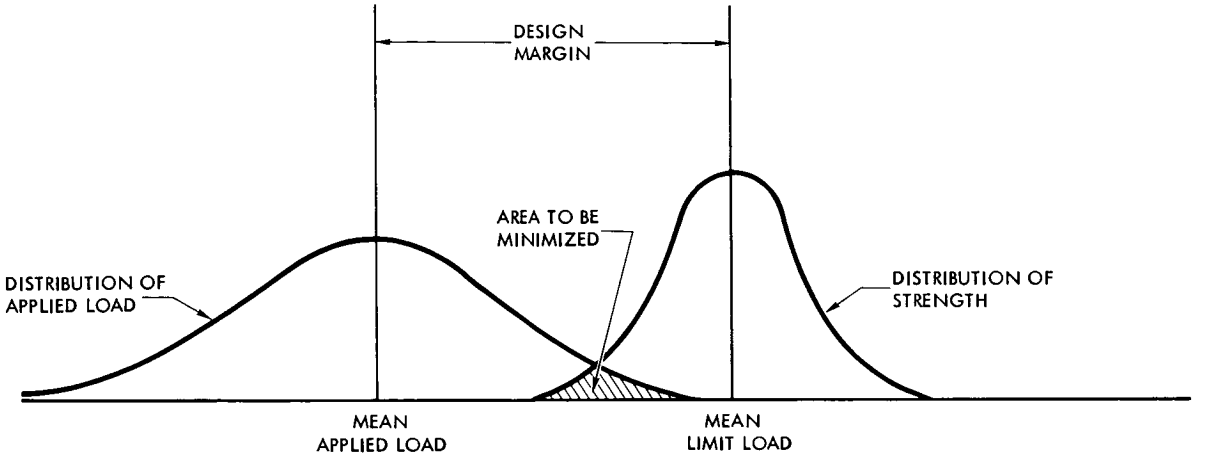


Figure 3-2. Design Margin Concept

Another example of derating employed on Apollo is the use of derating curves. An example of derating curves on electronic parts is presented in Figure 3-3. These curves are available on many Apollo parts and are employed where applicable. Equivalent derating factors are used from other space programs, such as Minuteman, when Apollo derating curves are not available.

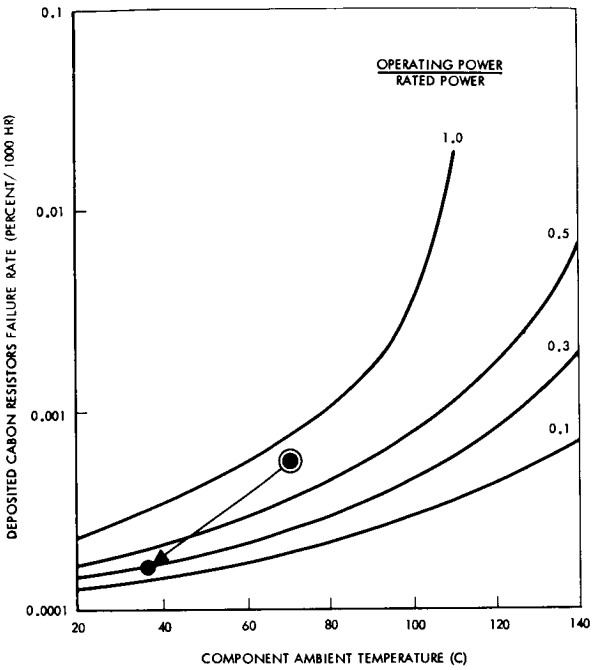
Use of Redundancy

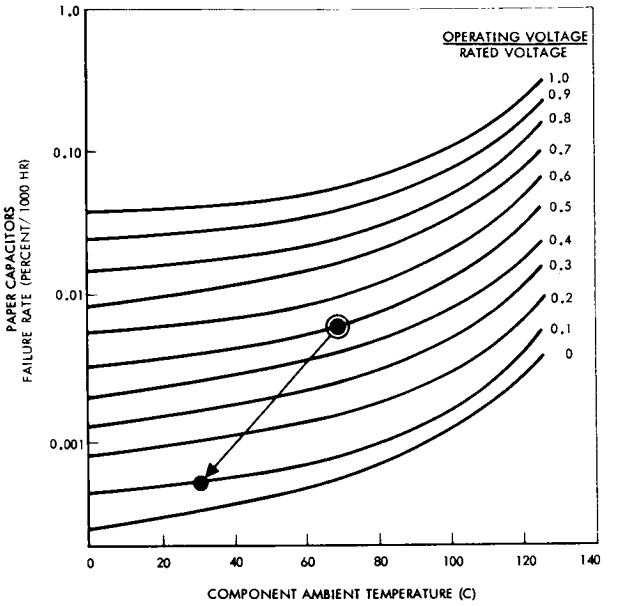
Part Level

The use of redundancy in component or circuit board design is a complicated procedure where no hard and fast rule can be applied. Each component will be carefully examined as to the desirability and applicability of redundancy, and its relationship to mission success and crew safety requirements.

The quad configuration, which will be defined and briefly explained, is an example of a redundant technique. Reliability formulas of various quad configurations will be supplied to design engineers. Normally quad redundancy consists of basic building blocks consisting of one transistor quad, three diode quads, and one load resistance. These are illustrated in Figure 3-4.

The following conclusions are noted as design considerations when a quad configuration is used.





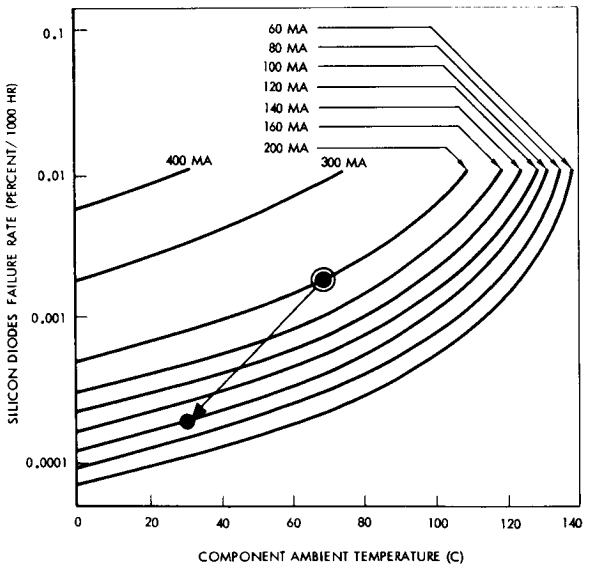
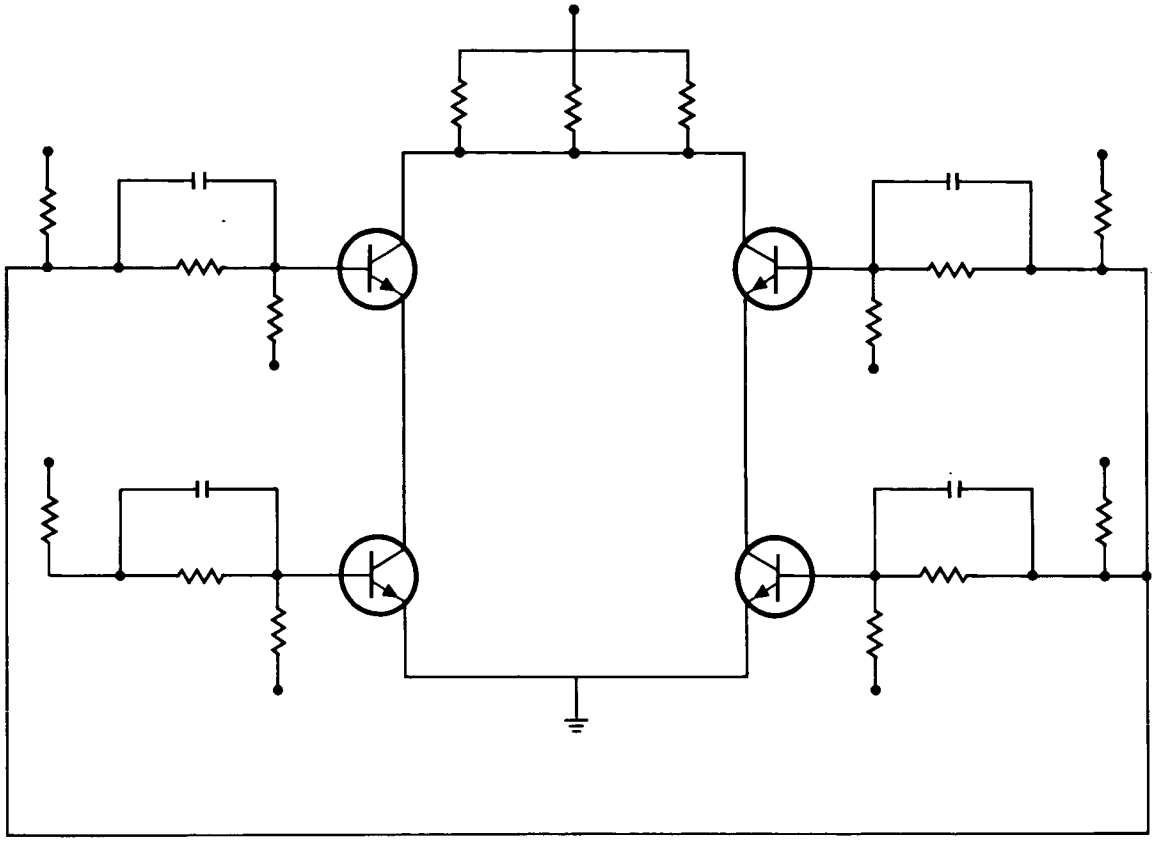
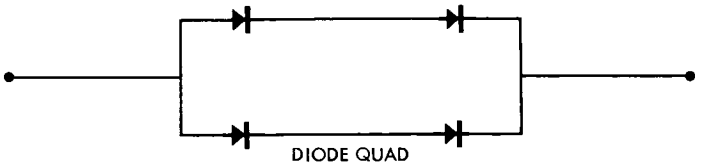


Figure 3-3. Example of Derating Curves on Electronic Parts





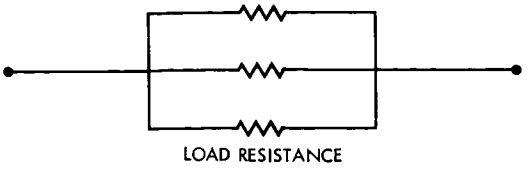


Figure 3-4. Normal Quad Redundancy

Advantages. The reliability of a basic building block for a 10,000-hour period can be increased from 0.995 to 0.99998 by using a quad approach. This represents an increase of mean-time-to-failure obtained utilizing the quad approach of approximately 250 times that obtained when no redundancy is used.

Disadvantages. The following are the disadvantages of the use of redundancy at the part level.

1. The quading of transistors subjects the operating parameters to more rigorous and demanding requirements.

2. The redundant design normally requires a supply voltage that is greater than that of the nonredundant circuit and therefore causes the minimum power rating to be about 2:1.

3. The quading approach is inherently slower, increasing signal propagation time by at least 2:1.

4. The redundant design dissipates up to, and possibly more than, four times the power if maximum speed is desired.

5. The redundant configuration can drive but one-fourth the load of a nonredundant circuit.

6. Failure of any unit of a quad can increase semiconductor power dissipation per unit up to four times. As a direct consequence, the resulting allowable ambient operating temperature is lowered.

7. A redundant circuit normally requires more weight and space than a nonredundant circuit.

8. A redundant part that fails in a redundant circuit may not be detected until both parts fail (i. e. , one part may fail before launch, producing a false apparent reliability but providing no redundant backup in flight). Because of these disadvantages redundancy will be employed on Apollo only when justified.

Subsystem Level

The use of redundancy in subsystems is accomplished in two ways. First, an identical component can be added to the subsystem by means of electronic or mechanical devices, or crew members can be utilized as switching elements; second, a dual capability can be provided by a crew member assuming the function of the failed system. Techniques are availabl

for determining the optimum redundancy at the system or subsystem level if such variables as weight, operating time, and probability of success are known. One such technique that will be applied to Apollo system redundancy is described in Appendix A.

Failure Effects Analysis

A failure effects analysis is performed on all spacecraft subsystems and components and on GSE mission essential equipment. The function of this analysis is to determine the modes of failure (i.e., the way in which equipments can fail), the subsequent effect that a component failure would have on a system, and the effect that the system failure would have on the spacecraft. This is done by determining the manner in which an item can malfunction (e.g., "short" or "open" circuit for electrical malfunctions and "closed" or "open" for mechanical malfunctions). Figures 13 and 14 present the forms that are used in documenting the results of analyses which are performed.

From the results of these analyses, reliability logic diagrams are constructed and mathematical models derived. Probability analyses can then be performed from which it can be determined if the system which is being analyzed has a reliability compatible with its requirement.

Additionally, the results of these analyses are used to determine the requirements for automatic/manual mission abort sequencing. This is done as a function of a degree of failure. Mission failures are potentially of three types: (a) catastrophic, (b) critical, and (c) deferred.

Mission failure, catastrophic. A failure occurrence such that the time between the failure event and subsequent hazard is less than 4 seconds. Abort sequence must be automatically initiated.

Mission failure, critical. A failure occurrence such that time between the failure event and a subsequent hazard is between 4 seconds and 2 hours, except for those failures which preclude the terminal transearth midcourse correction, which are to be considered as mission failure, catastrophic. Abort sequence must be initiated by switchable redundancy, either automatic or crew actuated.

Mission failure, deferred. A failure occurrence such that the time between the failure event and a subsequent hazard is greater than 2 hours. Abort sequence may be crew initiated.

NORTH AMERICAN AVIATION, INC. SPACE and INFORMATION SYSTEMS DIVISION

DATE: _____

PREPARED BY: _____

PAGE ___ OF ___

FAILURE EFFECTS ANALYSIS

ITEM	DRAWING NUMBER	ELECT. REFERENCE DESIG	FUNCTION	FAILURE TYPE	MISSION PHASE	FAILURE EFFECT ON COMPONENT PERFORMANCE	FAILURE EFFECT ON SUBSYSTEMS PERFORMANCE	FAILURE EFFECT ON APOLLO	POSSIBLE CREW ACTION
(Component by part name, manufacturer, and manufacturer's part number)	(Schematic or block diagram of the part)	(Code from schematic or diagram)	(Function of part, and when needed during the mission)	(Functional manner of probable part failure)	(Operation time as a percent of mission time)	(Effect of the failure on the component performance)	(Effect on next item or items in system and impairment of system function)	(A statement such as "mission loss," mission aborted," or "electrical power lost," etc.)	(Crew action which may overcome the effect of the failure)

FORM 963-Z-1 NEW 11-62

Figure 3-5. Sample Failure Effects Analysis

NORTH AMERICAN AVIATION, INC. SPACE and INFORMATION SYSTEMS DIVISION

NORTH AMERICAN AVIATION, INC. SPACE and INFORMATION SYSTEMS DIVISION

DATE: _____

PREPARED BY: _____

SYSTEM: _____ CRITICALITY RANKING PAGE ____ OF ____

ITEM	CODE	FAILURE TYPE	VEHICLE LOSS PROBABILITY	FAILURE MODE FREQUENCY RATIO	PREDICTED FAILURE RATE/ MISSION	CRITICALITY	REACTION TIME
(Component by part name, manufacturer, and manufacturer's part number)	(Reference to all items in the symbolic logic block diagram)	(Functional manner of probable part failure)	(Change in the applicable system crew safety reliability for a change in item reliability)	(Probability of occurrence of a particular mode divided by the item reliability)	(Predicted unreliability number consistent with the supplier's experience and other known information)	(Product of Vehicle Loss Probability, Failure Mode Frequency Ratio, and Predicted Failure Rate/Mission)	(Estimate of the Reaction Time for each failure mode)

FORM 963- Z NEW 11-62

Figure 3-6. Sample Criticality Ranking

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Data to Support Design Revisions

At the time any design revision is initiated, the failure effects analysis is simultaneously revised. The form is properly identified so that it can readily be correlated with the original form of which it is a revision.

Data to Support Design Reviews

A full set of completed failure effects analysis forms is included with the package of data in support of the S&ID design review program. The results of failure effects analyses then form a major part of the design review program.

Fail-Safe Provisions

When components or subsystems are designed, attention is given to those subsystems which are essential to crew safety to assure that proper fail-safety has been designed into the hardware. The reliability/design analysis checklist shown in Appendix C contains elements that will be used to meet the fail-safe provisions of each design. In addition, the failure effects analysis program and subsequent performance of probability analysis provide analytical tools by which the design can be quantitatively evaluated and compared with requirements. Provisions to preclude propagation of failures are investigated early in the design and subsequent worst-case tolerance analyses are performed to assure that proper clearances are provided. Again, the failure effects analysis program provides the tool by which the modes and effects of failures can be evaluated and weighed against subsequent crew actions.

RELIABILITY STRESS AND PARAMETER VARIABILITY ANALYSES

During preliminary design, the method of adding parts failure rates as a function of their stress and environmental conditions will be used to determine component failure rate. As the designs become more definitized, more sophisticated types of analyses will be utilized to determine both the stresses and the failures caused by accumulative tolerance build-up. Additional techniques will be employed to determine suitability and tolerability of the design. For electronics systems, these will include d-c, a-c, and transient design analyses, utilizing both linear and nonlinear techniques. Similar techniques will be utilized for mechanical systems. Each of these methods is presently being used by NAA Design and Reliability Engineers, and all can be accomplished on the 7094 computer.

Reliability Stress Analyses

These are performed on mechanical, electrical, and electronic subsystems to assure that stress levels are consistent with reliability requirements. The criterion for this evaluation is to assure that the stress levels and safety factors are consistent with required failure rates for the nominal condition and to further assure that, for the worst combination of tolerance build-up, no part is being stressed beyond its rated level.

Parameter Variability Analyses

These analyses assure that changes in part parameters due to drift or initial tolerances will not cause a module or component to operate outside of its performance limits. The purpose of the analyses is to preclude failures due to these variations and to assure that spares can be inserted in flight, without readjustment, to meet system performance requirements.

Method of Analysis

There are two reliability tolerance analysis methods, specifically aimed at determining the soundness of a design. These methods are adaptable to large computers (7094) or small general-purpose computers. Listed in order of sophistication, these methods are mandex worst-case analysis and parameter variation method.

By representing the circuit as a mathematical equation, the functional relationship between random parameter variation and circuit output variation is determined. These analyses, performed in minutes by a computer, closely simulate thousands of hours of breadboard investigation. Any mechanical or electromechanical component function that can be described by an analogous circuit function can be analyzed by either of the two methods.

An analysis is a cooperative effort between design engineers, parts specialists, experienced analysts, and computer programmers. The general flow of information is shown in Figure 3-7. Briefly, all methods of circuit analysis are comprised of the following steps:

1. Drawing one or more equivalent circuits, depending on the number of states the designer desires to investigate

2. Writing circuit equations and requirements in terms of part parameters

3. Incorporating the equations, requirements, and expected part-parameter variation ranges into a general computer program

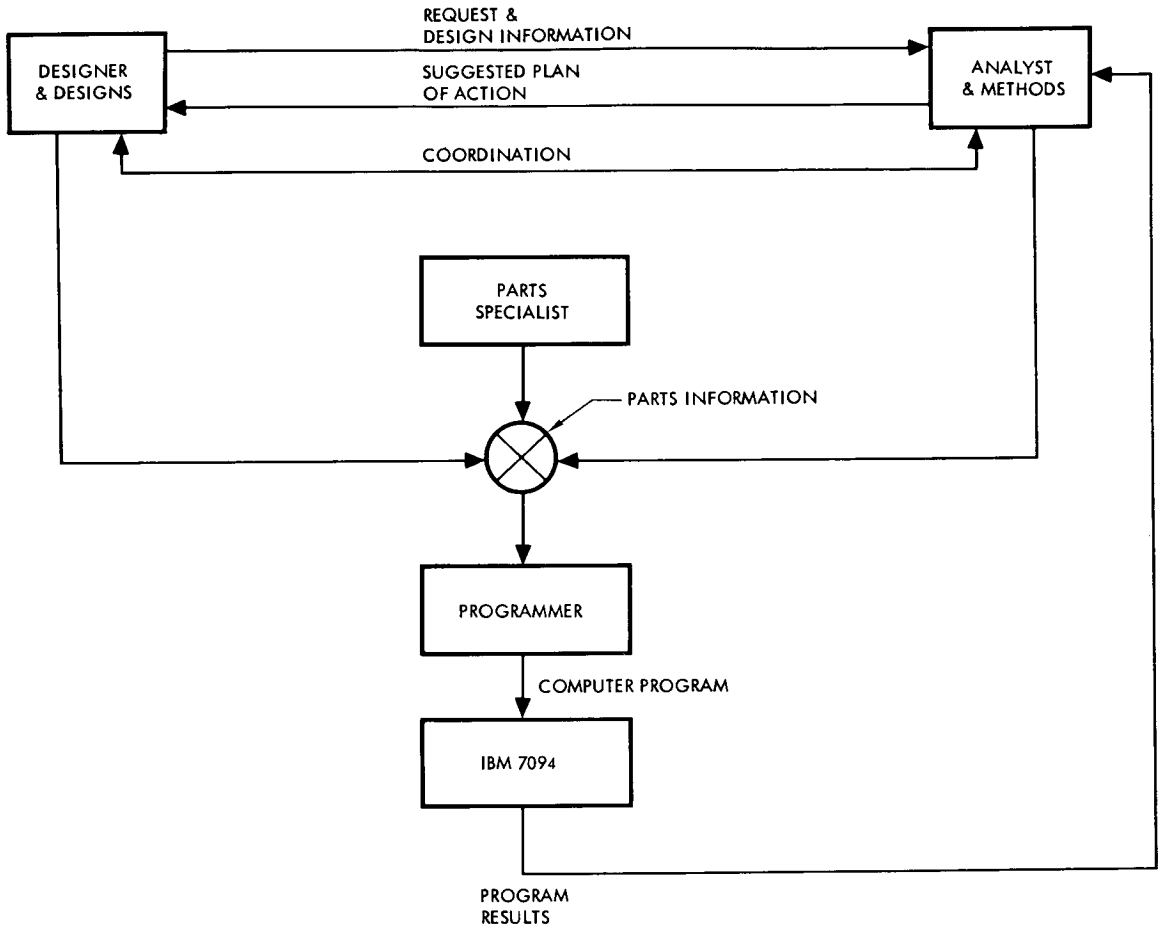

Figure 3-7. Information Flow for Machine Program Analysis Techniques

4. "Debugging" and running the computer program

5. Analyzing the computer program results

In some cases there is no need for a programmer, as when the design is simple enough to be programmed on a small computer, and the analyst has knowledge of the computer operation.

Except for preparation of individual part-parameter data, the initial phase of analysis is the same for all methods. First, an equivalent circuit is drawn as a linear representation of the physical device. This equivalent circuit should include circuit inputs and outputs and should take load impedance, input signal, and input generator impedance into consideration. Equivalent circuit equations relating the part parameters to the output parameters are then formulated and reduced to matrix form. Different equation representations are developed for circuits using multistable devices, such as diodes and transistors, which have two or three states. Computer logic is written to cover these changes of state. The equations are then verified by solving them on a small computer and comparing the results with data from the breadboard model. If the computer solutions and the breadboard data are not compatible, it may be necessary to alter the equivalent circuit so that it represents the physical circuit more accurately.

Description of Analyses

The selection of methods is a function of the type of circuit to be analyzed and the nature of the information desired. A brief description of two analysis methods is contained in the following paragraphs.

Worst-Case Analysis. The worst-case technique of analysis is based upon the philosophy that, if a circuit performs its functions and the parts are not overstressed with each specified output parameter within tolerance when all of its part parameters as well as input signal, power, and environment are at their worst-case values, then the circuit will perform satisfactorily and have adequate reliability for a less stringent set of conditions. The worst-case values are defined as those values which are equal to their tolerance limits but which tend to affect an operating parameter of the circuit in the most adverse manner possible and increase the stresses to a maximum.

The analysis is performed by setting each input parameter* at its highest or lowest allowable value depending on which effect is worst for the case being investigated. For an electronic circuit, this is accomplished as described in the listing on the following page.

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* Input parameter is any design parameter whose value is predetermined by the designer and is not a function of the circuit configuration

1. The eight-point central derivative theorem is employed to determine the various partials (e.g., $\partial V_{out}/\partial P_{in}$, where V_{out} is an output parameter and P_{in} is an input parameter).

2. Those parameters that gave positive partials are set at their maximum values, while those that gave negative partials are set at their minimum values. This will result in a worst-case configuration for a particular output variable.

If all the outputs remain within specification limits and the parts are not overstressed, then the circuit is classified as acceptable. If either the voltage variation or the phase shift is larger than specifications permit or parts are overstressed, the circuit is classified temporarily as a failure.

Because the worst-case method is a pessimistic analysis, the circuit should not be immediately rejected if the circuit variables are reasonably close to the specification limits. More realistic analyses can be performed to determine if redesign is actually necessary. The parameter variation is then used as a back-up analyses. A sample circuit analysis utilizing the worst-case technique is contained in Appendix B.

Parameter Variation Analysis. In the parameter variation method of circuit analysis, two input parameters are simultaneously step-varied within predetermined limits. After each step, the circuit equations are solved to determine the combined effect of the variations on the selected output and stresses. Input level variation is limited to the range of values expected from the preceding stage or circuit. Part variations are limited to the ranges of values expected for typical, nonfailed parts over the expected lifetime of the circuit. The calculated output values and the input values are recorded and can be used to develop what is known as a "schmoo" plot. The schmoo plot is a graphical representation of circuit failure points as the input parameters are varied, two at a time, from nominal. The schmoo plot furnishes a picture of the safe operating envelope for two-at-a-time parameter variation combinations.

The parameter variation method does not require extensive, large-sample life test parts data. However, small-sample accelerated test data are most helpful for determining part-parameter variation ranges. The mean values and assumed drift percentage of the input parameters complete the data necessary to give the designer a good indication of how his circuit will behave throughout its life expectancy.

IV. APOLLO DESIGN REVIEW

The Apollo reliability program includes a procedure for review of Apollo design, selected end items, associated equipment, test and certain production facilities, operations, and processes used in accomplishing the objectives of the overall Apollo program. Such reviews are conducted by a Design Review Board established for this program. The board reviews all aspects of design to identify problem areas affecting quality, safety, manufacturing, test operations, human factors, maintainability, facilities, logistics, producibility, and reliability. The board defines required actions to resolve the problem areas identified.

REVIEW BOARD

The Design Review Board is presided over by the program Reliability Manager for the Chief Engineer, and consists of the following program and support personnel:

Logistics Manager
Manufacturing Manager
Material Manager
Quality Control Manager
Reliability Manager - Chairman
*Responsible Design Manager
*Responsible Design Chief
*Responsible Design Supervisor
*Responsible Design Engineer
SMD Engineering Supervisor, Manufacturing
Test and Operations Manager

Additional personnel such as responsible interfacing system engineers, project engineers, or subsystem project managers are to participate as review members when requested by the board.

REVIEW CRITERIA

The Design Review Board chairman, through his group of design review specialists, normally schedules design reviews in three sequential phases: preliminary, major, and application approval. The number of reviews is determined by the criticality of the area to be reviewed, as

*Personnel responsible for the design being reviewed

established by Program Reliability. Special design reviews may be scheduled by the Design Review Board chairman when requested by a permanent board member. Criteria for the three sequential stages and the special design review are as follows:

Preliminary Design Review

The preliminary design review for each design is convened prior to detail drawing preparation, and as soon as possible after the functional and environmental criteria have been established and the responsible designer has firmly established the design concept. The purpose of the preliminary review is to evaluate and approve the design approach, determine potential problem areas, and provide a basis for further reviews.

The data required for the preliminary reviews consists of:

1. Circuit schematics or charts of functional components for both electrical and mechanical systems or equipment

2. Environmental and performance criteria which are used in the determination of environmental stresses and the performance requirements of the equipment

3. Preliminary failure mode analysis

4. Reliability apportionment (including the major system elements). The allocation of the reliability quantative requirements to the subassembly level is in accordance with stress factors and complexity which have the greatest influence on the subassembly

5. Principles of operation which include the design principle of the equipment and the details of how it will do the job it is intended to do

6. Maintainability criteria, consisting of design proof that the equipment, during specified maintenance periods, can be restored to operational conditions in minimum time

7. Data resulting from completion of checklists in all areas of Engineering, Reliability, Quality Control, Test, Manufacturing, Logistics, and Material

8. Applicable customer, NAA, or supplier specifications, exhibits, or other documents, when available

Major Design Review

The major design review is normally conducted prior to the final release of all drawings defining the design to be reviewed. The release of engineering drawings, specifications, and supporting documents, however, proceeds according to established procedures, and is not delayed pending completion of the major design review. At this time, the design has progressed to a stage that components may be physically and functionally defined, system and component interfaces delineated, and manufacturing, quality, test, and operational requirements defined. During the major design review, the functional, reliability, operability, maintainability, quality, and producibility aspects of the design are evaluated and approved, or actions required to eliminate weakness are defined.

The data required for the major design review consists of:

1. Specifications delineating design criteria which are used during the design effort to provide the required integrity of the equipment
2. Detailed layouts defining physical interfaces and characteristics
3. Detailed analyses delineating physical and functional parameters and tolerances
4. Test operations and maintenance plans for the equipment during development, manufacturing, and operations
5. Reliability apportionment and prediction reports covering equipment reliability
6. A statement of environments which include all the environments in which the equipment will operate
7. A manufacturing plan covering fabrication and quality requirements
8. Data resulting from completion of design review checklists in all areas of Engineering, Reliability, Quality Control, Manufacturing, Logistics, and Material
9. Completed quality implementation plans
10. Failure mode analysis

11. An analysis of the human factors associated with the equipment, including the elimination of such predicted errors as maladjustment, misalignment, mismatching, and misuse.

Application Approval Design Review

The application approval design review is conducted following 100 percent design release and completion of application approval testing to a point allowing utilization of applicable data for the review. By this time, the design is completely defined so that any aspect may be evaluated in detail. Program management in Test and Operations, Quality Control, Manufacturing, Logistics, Material, Engineering, and Reliability functions have analyzed the design and prepared detailed evaluations of the application of the design in program operations.

The application approval design review provides final and conclusive acceptance of the design, and records reflecting results of testing, quality control, manufacturing, and logistics operations conducted to assure a reliable application in the program. When a problem or discrepancy is not resolved, it is reported to the Chief Engineer, and application approval of the design is withheld until corrective action is complete.

The data required for the application approval design reviews consists of:

1. Completed layouts, drawings, and details, as determined by the design review chairman and the responsible design functional representative

2. Data resulting from completion of checklists in all areas of Engineering, Reliability, Quality Control, Test, Manufacturing, Logistics, and Material

3. Completed and evaluated test specifications and test data

4. Completed tooling, manufacturing and handling plans, and resulting data

5. Completed quality implementation plans, and resulting data

6. All pertinent component and system specifications

7. Failure mode and effect analysis

8. Reliability apportionment and prediction reports

9. Completed detailed reliability analysis and assessment

10. Completed procurement specifications

11. Maintenance plans

12. Human engineering analysis

13. Systems integration analysis

Special Design Review

In addition to the regular sequential design reviews, the Design Review Board Chairman may, upon receipt of recommendations from any of the permanent Design Review Board members, schedule a special design review. Special end item reviews of boilerplates and spacecraft are conducted on a preliminary and preflight basis. Written justification is required to substantiate special design review recommendations. Special design reviews are conducted to review S&ID or supplier designs not included in the regular design review schedule, changes in design or design application, quality, manufacturing, test or operations problems affecting design, and end item or associate contractor interface designs.

Depending on the nature of the design, special design reviews may be completed in one stage or may require scheduling the normal three sequential reviews.

Data requirements for special design reviews are designated by the Design Review Board chairman and include, but are not limited to, the requirements established for preliminary, major, or application approval design reviews.

REVIEW CHECKLIST

The Reliability/Design Analysis Checklist used during the design review is contained in Appendix C.

AREAS TO BE REVIEWED

Design reviews will be accomplished on all spacecraft subsystems and equipment as well as mission essential ground support equipment and end items of spacecraft and boilerplate test hardware.

BOARD MEETING DISPOSITION

Disposition of a design is made during the Design Review Board meeting as follows:

1. Design approved without qualification

2. Design approved, subject to satisfactory resolution of action items

3. Design approval withheld. Approval may be withheld for lack of sufficient data to evaluate the design, interface problems, material considerations, etc. A review must be scheduled to cover areas requiring improvement

4. Design disapproved. Complete inadequacy is required to disapprove a design. Another review of the modified or changed design approach is necessary

5. When one or more board members strongly disagree with the remaining board members, a minority report is submitted to the Chief Engineer

Problems which the board is unable to resolve are referred to the Chief Engineer. In these instances, the Design Review Board chairman provides all of the necessary data, including clear definitions of the problem areas.

The Chief Engineer takes such action as necessary to resolve the problems. The design is then reviewed again by the board. In all instances, final authority rests with the Chief Engineer.

REVIEW REPORTS

The chairman of the Design Review Board is responsible for the preparation of reports documenting Design Review Board activities. These reports are submitted to the Chief Engineer, Design Review Board members, and meeting participants, and summarize the data submitted to the board for design review and reflect board dispositions, corrective action taken, and board approvals.

V. RELIABILITY MONITORING AND DOCUMENTATION

Timely reviews of progress, status, data, and reports are essential to the successful implementation of corrective action and the management of the program. Accordingly, a reliability monitoring, program review, documentation, reporting, and data processing system has been established to provide NASA and S&ID functional organizations and management with significant information and guidance upon which decisions can be based.

MONITORING

The Apollo Reliability Manager is responsible for monitoring the progress of all reliability activities, including preparing and submitting to higher management all reliability documents and reports. He will also review and approve other reports related to reliability and containing reliability information.

The paragraphs that follow delineate the responsibilities and the scope of the data program and activities as applicable to Apollo.

Reliability Manager

The Apollo Reliability Manager will keep informed of reliability program progress by continuously monitoring and periodically reviewing all reliability activities. The data and reports generated by the documentation and reporting system will be his source of information. From these and other sources, the manager will determine whether the reliability/crew safety objectives are being attained, that the program plan continues to be adequate as it progresses, and that all work affecting reliability is being performed in accordance with the program plan. He will also determine whether past reorientation has been effective and whether control measures and corrective actions are adequate.

The Reliability Manager will provide reliability program progress information and data for periodic MSC technical and management program progress reviews.

Formal determinations of progress will be made and published in the quarterly reliability report along with implemented or recommended corrective action as applicable. Charts, including those showing achieved reliability versus reliability growth objectives, will be maintained and continuously displayed.

Reliability Data

Reliability data will be extensively employed as a management tool for control and direction of the Apollo program. Data are continuously accumulated, collated, and analyzed to show trends and status and to allow predictions in all development and test areas. Reliability data for management purposes, as well as for technical and analytical purposes, flow in the manner indicated in Figure 5-1. A description of nonconformance and failure reporting, nonconformance analysis reporting, and corrective action reporting systems appears in Section VIII of this plan.

Data Center

The primary function of the data center (Apollo Data Control) is to establish and maintain a central S&ID operation for acquisition, processing, storage, retrieval, and dissemination of data from Design, Test, Manufacture, Inspection, Subcontractors, Associate Contractors, and Operations areas. Figure 5-2 is a typical schematic presentation of Apollo Data Control central data function.

Basic equipment to be employed in data processing will consist of the IBM 7094, 1401, 1410, and 1301 and the Stromberg Carlson 4020 computers, supplemented by a portable IBM 1620 for increased flexibility. These computers are programmed to provide information and compilations and to perform special search and analysis functions, such as the following:

Nonconformance reporting data for corrective action and follow-up
*Evaluation and analysis for design or quality improvements, reliability audits, and progress reporting
Component usage data
Equipment functional histories
Supplier quality history lists
Reliability assessments
Correlation of failure mode and cause data
Configuration and serialization records
Operating time records
Subcontractor and supplier ratings
Qualification status reports
Specification lists
Test results
Corrective action summaries and status
Critical and limited-life parts list

These data are periodically distributed to those directly affected.

*Parameter variation, worst-case analysis, logic networks, failure mode analysis, Monte Carlo analysis, etc.

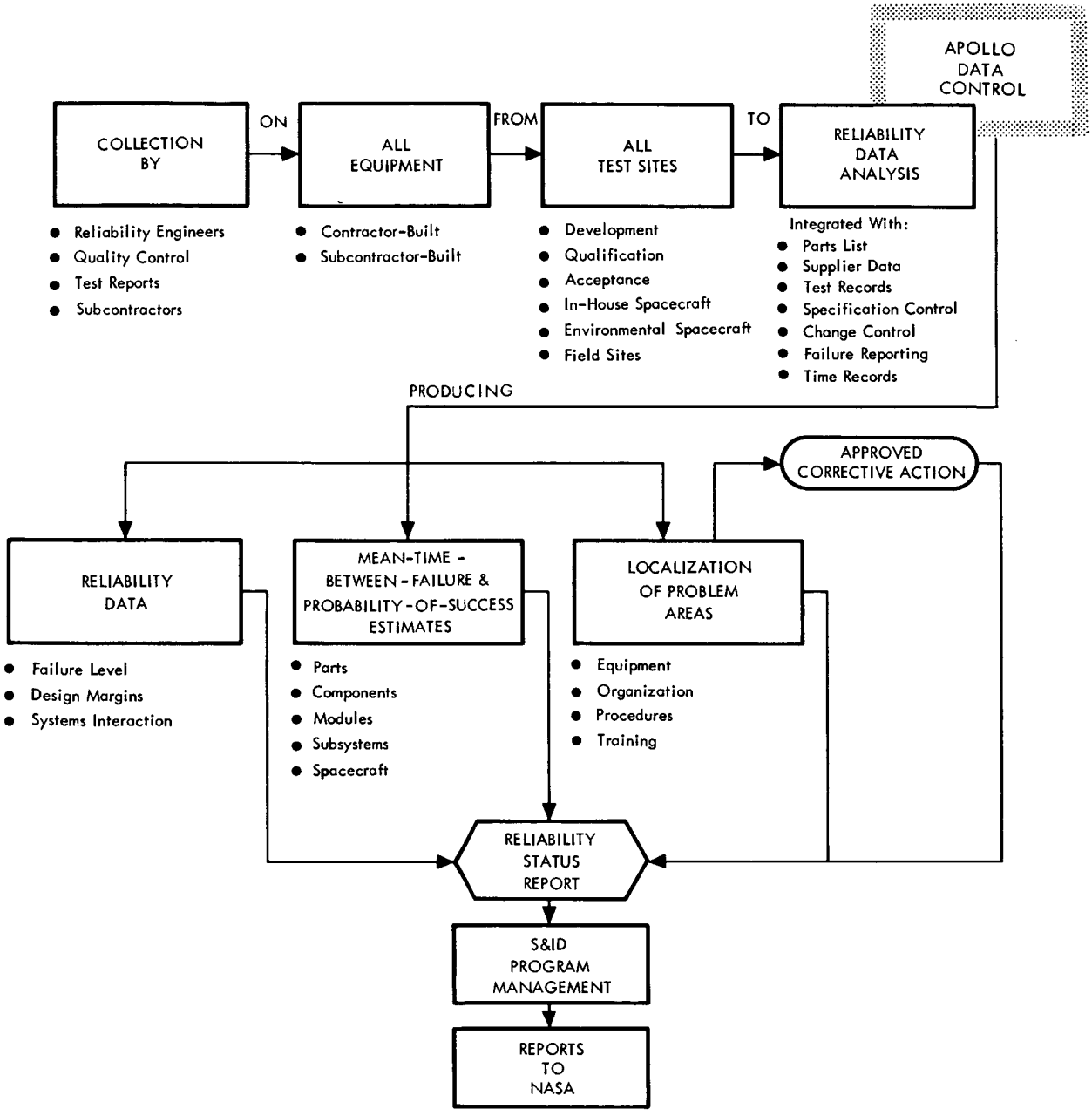


Figure 5-1. Data Acquisition and Analysis Flow

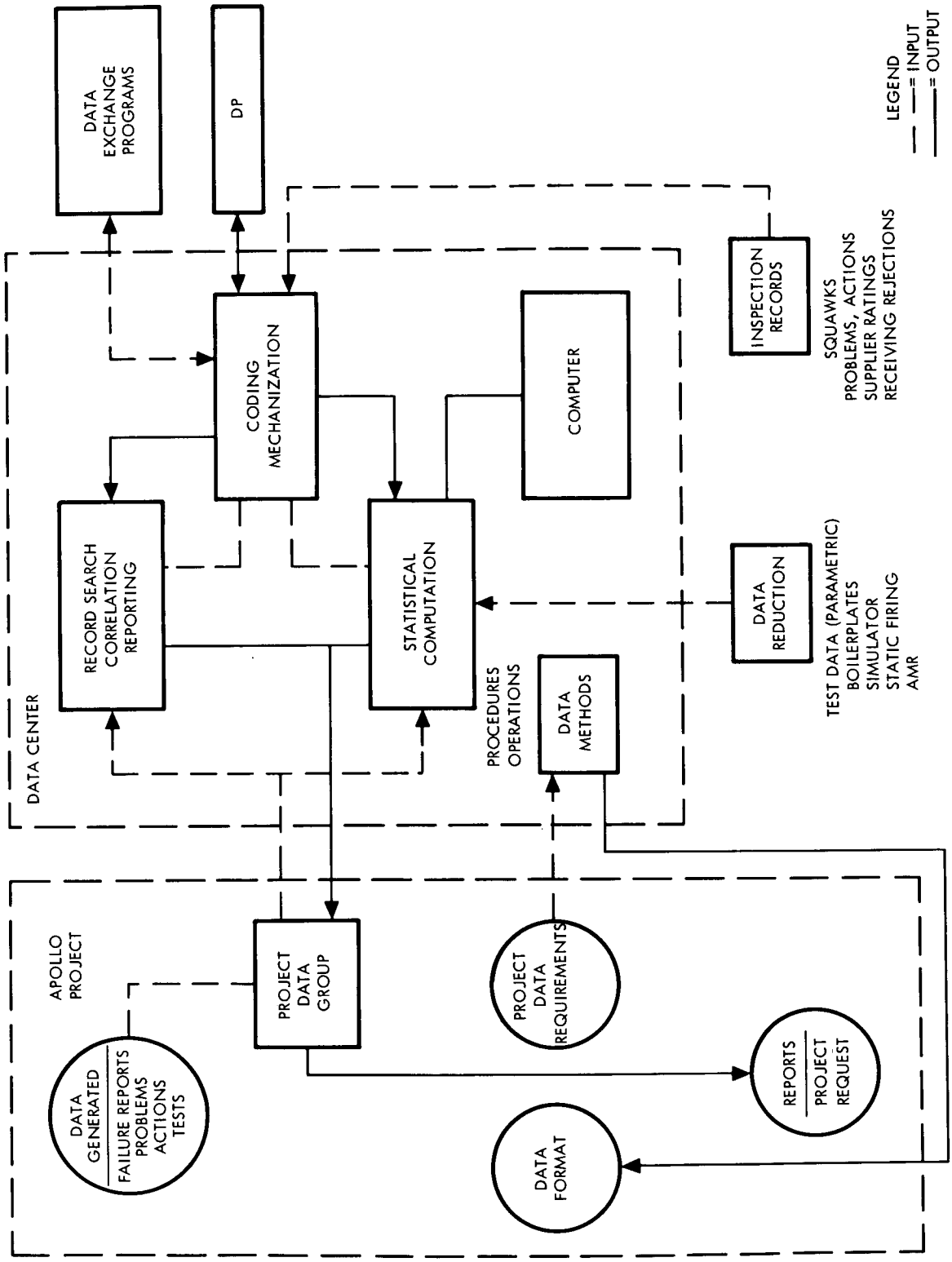


Figure 5-2. Data Management, Central Data Function

Computer Support

The Computer Support Group under the direction of the Reliability Director is responsible for writing, documenting, and maintaining the digital computer programs required by Apollo Reliability for apportionment, prediction, assessment, and the statistical evaluation of data. Technical requirements for the digital programs are originated within the appropriate Apollo Reliability area under guidance of the Apollo Reliability Manager.

DOCUMENTATION AND REPORTING

The documentation and reporting system provides periodic reports for S&ID and NASA to permit a continuous accounting of reliability progress and problems throughout the program. Reliability documentation and reporting are in accordance with Exhibit I of the Definitive Contract NAS 9-150 and include the documents listed in Appendix E. Documentation and reporting requirements of specification MIL-R-27542 are met by including the desired information in reports required by Exhibit I of the Definitive Contract NAS 9-150.

VI. ASSOCIATE AND SUBCONTRACTOR RELATIONSHIPS

This section establishes the means for assuring that the reliability of subcontracted work and the work of associate contractors is consistent and compatible with over-all system objectives.

ASSOCIATE CONTRACTORS

NASA will select associate contractors for the space laboratory module, lunar excursion module, navigational and guidance system, flight research and development instrumentation, scientific instrumentation, and NASA-furnished crew equipment. Consistent with NASA requirements the Apollo Reliability Manager will determine the scope of effort required to assure compatibility of S&ID-associate contractor interface and integration requirements. Under his direction, Reliability Engineering personnel will accomplish the following:

1. Maintain effective liaison between associate contractor and S&ID and assist them in the solution of reliability problems

2. Participate in a joint effort with associate contractors and, in close coordination with NASA-MSC, specify in detail requirements for module and equipment interfaces with ramifications in reliability or crew safety

3. Advise NASA on the acceptability of associate contractors' designs for compatibility with over-all spacecraft reliability and safety requirements

4. Coordinate on integrated systems reliability and crew safety analysis

5. Coordinate data requirements and data exchange

6. Coordinate and establish common usage components and parts lists

7. Coordinate test planning to assure program optimization

8. Provide associate contractors with reliability feedback information

MAJOR SUBCONTRACTORS

Major subcontractors are required to establish a reliability program in consonance with paragraph 2.4 Exhibit A of the Definitive Contract NAS 9-150 and military specification, MIL-R-27542, and to prepare reliability program and qualification test plans. Plans are reviewed and approved by S&ID. Currently designated as major subcontractors are the following:

Aerojet-General	Service propulsion subsystem
AiResearch	Environmental control subsystem
AVCO	Heat shield
Beech Aircraft	Cryogenic storage subsystem
Collins Radio	Telecommunications subsystem
Lockheed	Launch escape motor
Marquardt	Service module reaction control subsystem
Minneapolis-Honeywell	Stabilization and control subsystem
Northrop-Ventura	Earth-landing system
Pratt & Whitney	Fuel cells
Rocketdyne	Command module reaction control subsystem
Thiokol	Escape tower jettison motor
Autonetics	Spacecraft instrumentation test equipment

The reliability programs of each major subcontractor are essentially the same, since all are based on the requirements of MIL-R-27542 and NPC 200-2 and require NAA/S&ID approval prior to application to the Apollo Program. Some variations occur, however, because subsystem characteristics are different, the state-of-the-art is more advanced, or the subcontractor's reliability requirements are more stringent. Such factors have been brought to light in the preaward subcontractor reliability surveys. The scope and format for preaward surveys are defined in Appendix F. All controls, provisions for liaison and surveillance, documentation and reporting, data analysis, review, training, and motivation are established and delineated in detail in the Statements of Work, Documentation Requirements Specifications and in the required plans. Consistent with NASA requirements, the Apollo Reliability Manager determines the scope of contractor reliability programs and efforts. Under his direction, Reliability Engineering personnel will accomplish the following:

1. Assist pertinent functional divisions in the selection of qualified subcontractors and suppliers

2. Prepare reliability requirements for statements of work, documentation specifications and procurement specification for subcontracted items

3. Evaluate proposals from potential suppliers of Apollo equipment. Support contract negotiations on reliability activities.

4. Monitor subcontractor reliability and test effort

5. Review and approve subcontractor reliability program, acceptance and qualification test plans

6. Maintain effective liaison between subcontractors and S&ID and assist them in the solution of reliability problems

7. Provide subcontractors with reliability feedback information

8. Provide reliability inputs to and review reliability portions of procurement documents prior to release

Monitoring and Coordination

Reliability engineers with specialized experience in the various subsystems are assigned to monitor reliability program progress at each subcontractor. The reliability engineer provides liaison between the subcontractor and S&ID.

Control

Before a major subcontractor is authorized to proceed with design or production, the following prerequisities must be met.

1. The subcontractor's engineering, reliability, manufacturing, and quality control personnel and capabilities are suitable for the development and/or production of highly reliable spacecraft or ground equipment.

2. The design is approved by S&ID for reliability, function, and manufacturing and quality feasibility.

3. The subcontractor's quality control and inspection plans are approved by S&ID.

4. The test plans and facilities used by the subcontractor are approved by S&ID.

5. The subcontractor's reliability program plan adequately sets forth the subsystem reliability approach and objectives.

6. Commensurate requirements and controls are transmitted to sub-tier suppliers

After authorization to proceed, the subcontractor's activities are under the surveillance of S&ID resident Quality Assurance (representing Reliability and Quality Control) and Design personnel. Close scrutiny is maintained over each element of the various program plans. Precise controls and documentation requirements serve as the basis for program analysis and review by both the subcontractor and S&ID.

Training and Motivation

Subcontractors are required to provide indoctrination and training in reliability and quality for all employees. Initial orientation briefings are given at the time individuals are assigned to the Apollo project. Briefings continue periodically for the duration of the program. The purpose of the briefings is to establish an understanding of the Apollo missions, to point out the relationship of the hardware and personnel to completion of this portion of the national space program, and to establish the motivation to guarantee excellence of job performance. Through training activities, subcontractors will establish and sustain high skill levels for personnel associated with all phases of development, production, and test. Symposia are presented by S&ID for subcontractors to provide educational material and for program requirement clarification. Additionally, subcontractors are provided with publications, films, guidance and training course material to develop a reliability educational program. A description of S&ID's responsibility for subcontractor indoctrination and training is given in Section X.

OTHER SUBCONTRACTORS AND SUPPLIERS

Depending upon the reliability requirements and the complexity of the item to be purchased, the Apollo Reliability Manager establishes the requirement for a formal reliability program at other subcontractors and suppliers. The reliability requirements in the Statement of Work or procurement documents specify the extent of the program.

VII. RELIABILITY ASSESSMENT

The Apollo test program is an integrated plan designed to provide for maximum utilization of data from each test area for developing and qualifying hardware and assessing achieved reliability of the spacecraft and GSE. Laboratory, ground spacecraft, and flight tests compliment each other to provide assurance that equipment will perform its intended functions during the manned phases of the program. Details of this test plan are contained in the Apollo General Test Plan, SID 62-109.

TEST PLAN DESCRIPTION

The high reliability and safety objectives, a desire for an assessment of achieved reliability, and the variety of mission environments make the performance of a single test to satisfy these requirements economically impractical. S&ID intends that most testing at the part, component, subsystem, and system levels be used to assess reliability and crew safety. Figure 7-1 defines the different phases of the overall Apollo test program and the approximate percentages of data from each test area applicable to the assessment of reliability. Although these percentages will vary with each item considered, they are representative of the expected averages.

The integrated test plan for Apollo is a consolidation of a sequence of tests starting with certain material evaluations and proceeding through actual flight and recovery of the spacecraft. Figure 7-2 illustrates the integration of the qualification tests into the overall test plan. Qualification testing of materials, parts, components, subsystems, and systems under functional and environmental stresses will, in general, follow development tests but will include certain development test results. Qualification tests will be conducted to ensure that the design is capable of meeting anticipated Apollo LOR mission requirements. Other tests on nonflight hardware will demonstrate capabilities of integrated systems and the complete spacecraft and their reliable operation under simulated LOR flight performance and environmental conditions.

Acceptance tests on flight hardware will verify that the performance, reliability, and quality of parts, components, subsystems, and spacecraft, as manufactured, are equivalent to previously approved items. The standards against which these items are compared will be determined from the results of development and qualification tests.

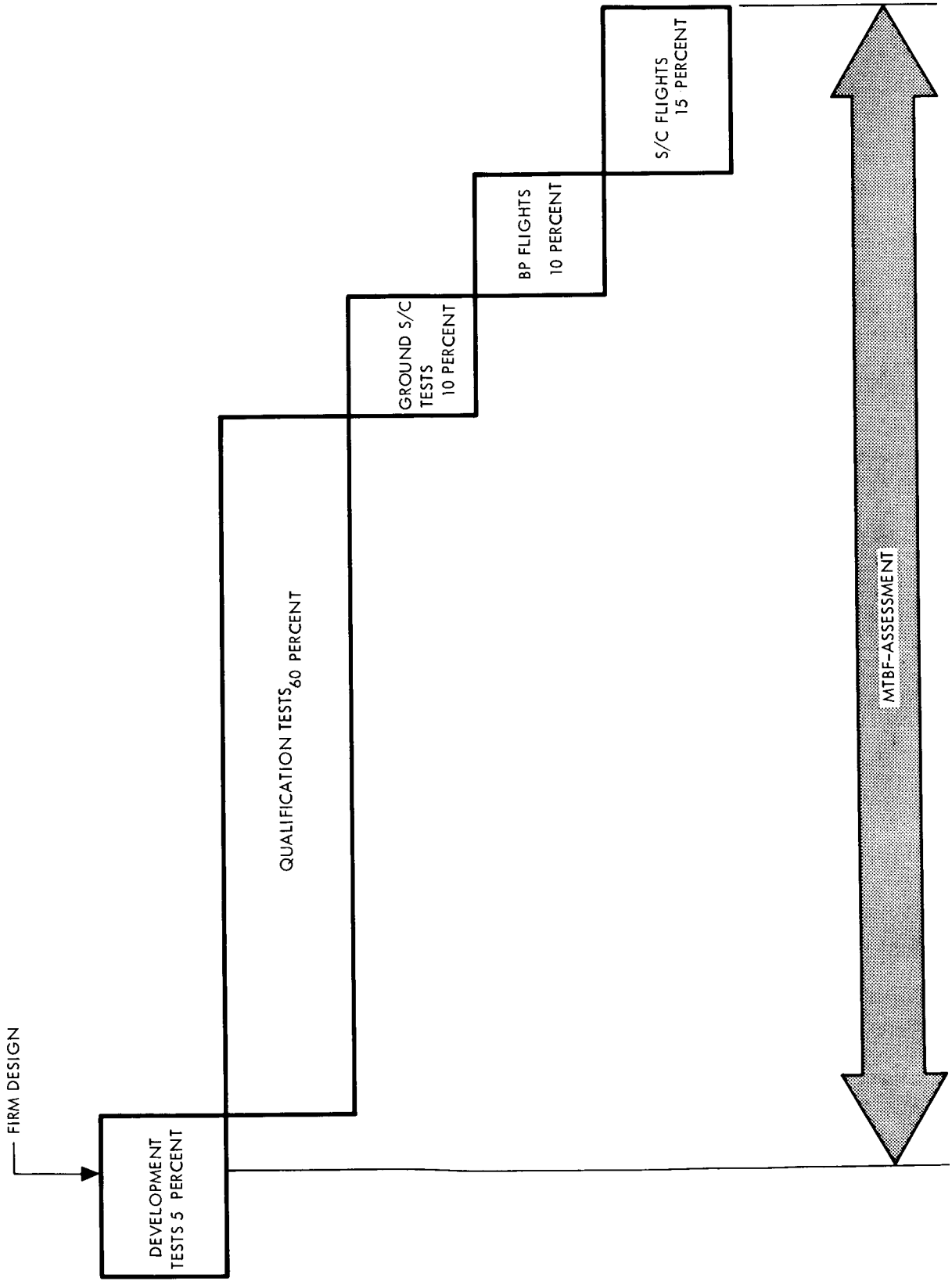


Figure 7-1. Reliability Assessment

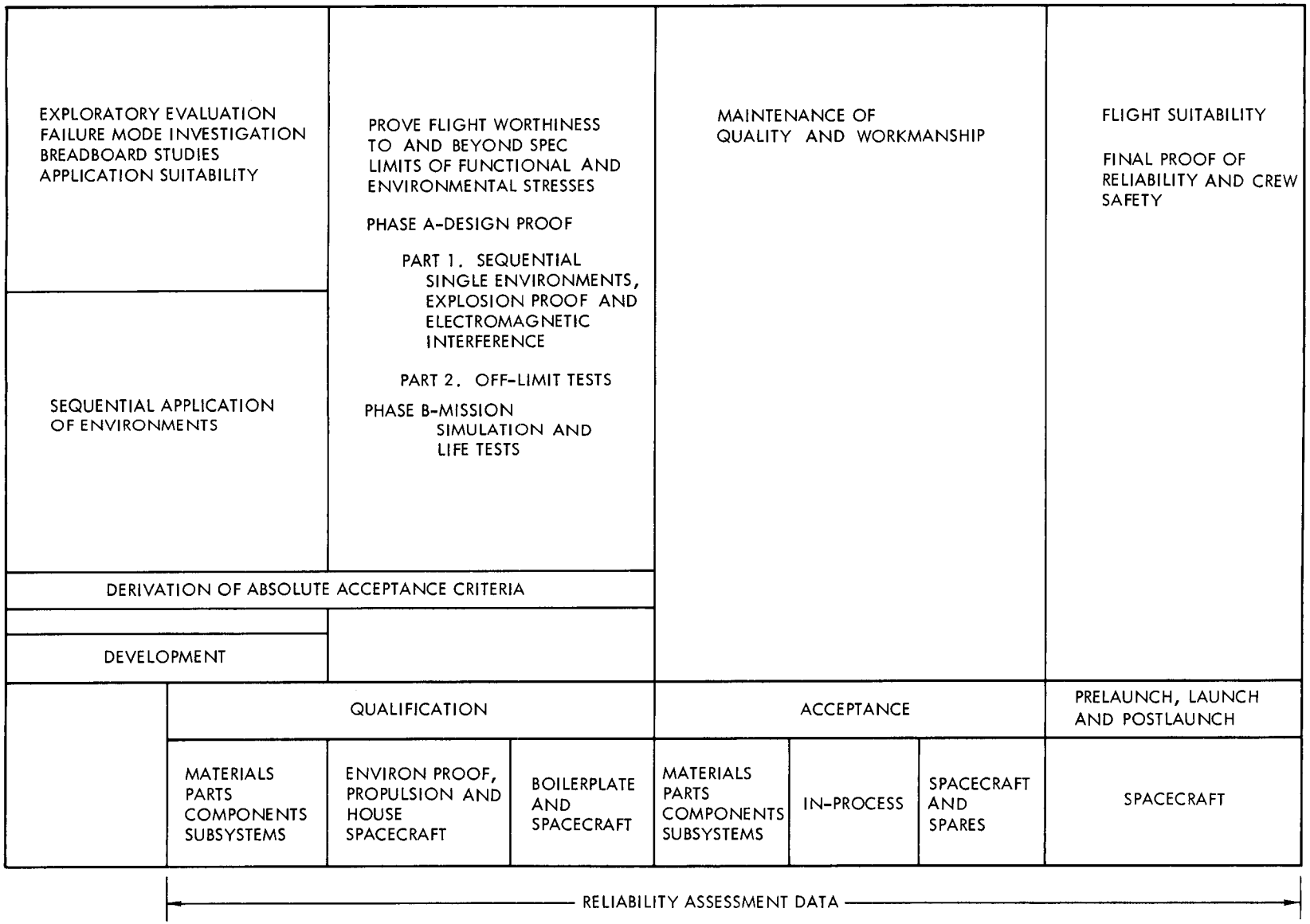


Figure 7-2. Test Definitions and Philosophy

A positive go, no-go criterion for decision will be established for use during general acceptance and prelaunch operations and will be employed to the greatest extent possible throughout the test program. Only by careful planning will it be possible to accomplish this integrated program and keep test expenses to a minimum. Due consideration will be given to ensure the required degree of flexibility in test planning and programs and the applicability and continuity of data at all levels of assembly through the complete spacecraft.

QUALIFICATION TESTS

Qualification tests will be conducted on all LOR equipment designed for use in the spacecraft command module, service module, adapter assembly, and associated ground support equipment. The qualification test plan provides for the maximum utilization of data from all ground and flight tests conducted throughout the Apollo program.

Although tests conducted during development of hardware may be considered preliminary qualification, formal qualification will not be initiated until reasonable assurance exists (from development tests) that the equipment will pass qualification requirements. The qualification test program will establish the flightworthiness of the equipment.

Quantitative and qualitative reliability analyses (logic networks, criticality, numerical predictions, and failure mode analyses) will be utilized to assign testing priority to equipment essential to crew survival and mission success.

Qualification tests are the fundamental tests for verifying the stability and integrity of the design for application and assessment of reliability. These tests are conducted on three major equipment groups: materials and structure, parts and components, and subsystems and systems.

Materials and Structures

Materials

Pre-qualification material suitability and compatibility tests will be conducted in areas where application data are lacking or when analysis reveals any suspicion of reliability or crew safety degrading potential. These material tests primarily are intended as preliminary investigations of materials proposed for any structure, part, or component. Included will be metals, adhesives, ablative materials, insulating materials, and metal sandwich structures. Two areas of particular interest will be the effect of hard vacuum on materials exposed to space environment and the effect of heat during reentry.

The effects of temperature and hard vacuum on seal materials will be studied and evaluated by either the supplier or S&ID prior to use of any seal material in the Apollo vehicle. Qualification testing of some materials in simulated mission environments will be performed. Statistical sampling methods will be used to select test samples of materials that may be susceptible to deterioration in these environments.

Formal qualification testing of materials, such as lubricants, seals, and potting compounds, will minimize test delays and failures on high-cost component and system testing and provide the needed assurance in the functional integrity of the materials used on the spacecraft. However, in general, the philosophy of testing at the highest practical level will be employed throughout development.

Structures

Structures will generally be exposed to mechanical stress tests to induce fatigue and/or determine weakness inherent in materials and design or due to manufacturing techniques and controls. Tests will be conducted to ultimate stress values while exposed to the critical environments for extended periods of time. Typical of equipment in this category are tanks, skin, reservoirs, accumulators, vehicle structure, ports, ingress and egress hatches, and heat shields.

In testing of metallic structures, the classical properties of interest will be verified. Specimens to be tested include plain and welded samples. Fatigue strength will be verified at approximately five stress levels for each test temperature. Standard specimens will be tested to evaluate static strength in block-shear, flatwise tension, flatwise compression, uniaxial and biaxial edgewise compression, and beam shear. At least five specimens will be evaluated in each test. Temperature fatigue strength of the material will be determined in block-shear and flatwise tension. Approximately four stress levels will be investigated for each type of loading at each test temperature.

Included in the list of properties to be monitored during the testing of metallic structures will be appropriate physical, mechanical, thermal, and electrical characteristics. Additional tests to demonstrate resistance to the effects of hard vacuum will be performed when required.

Parts and Components

The principal qualification test effort will begin at the part or component level. Part qualifications tests will be performed as necessary data are lacking and when economically or technically more advantageous than tests at the component level. However, such tests are expected to be

minimized by the use of resistors, diodes, and other parts of known high reliability in all possible applications.

Parts and components will be divided into the following three categories for qualification test planning purposes:

Category I	Newly designed parts or components for which no statistically valid test or experience data exist
Category II	Existing hardware for which partially satisfactory prior test and experience data can be provided, or Category III hardware that is to be modified for the Apollo application
Category III	Existing hardware for which satisfactory qualification test data or experience data already exist

All Category I parts or components will be subjected to testing, which in its initial phases will provide the data necessary for final development of the design. In the middle phase, the test plan will encompass the tests necessary for qualification. The final phase of the test plan will verify off-limit performance, performance variation under single and combined environments, wearout characteristics, and performance regression with time.

Category II parts and components may be subjected to sequential tests, which, together with prior data, will satisfactorily substantiate the qualification of each item used.

Except in a few special cases, Category III parts and components will, by definition, require no further testing. All existing test and experience data, however, will be carefully reviewed for substantiation of the complete suitability of the part or component for the intended application.

A detailed breakdown of the above categories will be shown in the Qualification Status List, SID 62-784 (see Appendix E). In order that this program may be implemented to obtain maximum data at minimum cost, each component type will be evaluated separately and a test plan will be prepared to assure each item's compliance with the requirements. A summary table will list the equipment to be tested, the number of test specimens, the type of test program to be performed, and the most critical environments and levels to be employed.

Subsystems and Systems

Subsystem and system tests will be planned to provide performance variance, off-limit performance, wearout data, and exploration of the effect

of such performance on system functional parameters. Interaction and interface problems between components and subsystems will be explored. Test times will be applicable to the subsystem or system, as necessary for the acquisition of valid data, to supplement or confirm the part and component test data. The objective will be to complete as much as possible of the part and component testing and data evaluation before starting tests of the subsystems or systems.

One-Shot Devices

Since one-shot devices have singular characteristics, such as limited operating life and selective current or force sensitivity, any lot may have wide variability in characteristics. The reliability of such devices can only be assessed by testing multiple samples to give a probability of functioning under imposed stresses and operating conditions of a LOR mission.

Although some one-shot devices may be tested in accordance with specification MIL-R-25535A, it is intended that most of these tests will be conducted in accordance with the general requirements outlined in SID 62-109. Sampling plans will be established to determine if the lot meets functional and quality requirements with a high degree of repeatability.

Ground Support Equipment

Ground support equipment items will be tested using plans similar to those for the spacecraft systems and subsystems. The amount of testing to be performed on each item will be based upon the criticality of the item and equipment characteristics, such as complexity, use history, previous testing, apportioned reliability, predicted reliability, and frequency and duration of operation. As with flight equipment, results from subsequent operations of the ground support equipment will be used in developing higher confidence in assessed reliability.

The test procedures prepared for each equipment item will designate the functional and environmental parameters, the associated tolerances, and the qualification test requirements. The tests will be conducted at the console level (mission essential items) except where analyses indicate that it is more practical to perform them on a critical sub unit.

TEST PLAN IMPLEMENTATION

The qualification tests of appropriate parts, components, subassemblies, and higher levels of assembly are to be performed to verify the inherent capability of the design to meet the LOR flight performance and environmental

requirements. The qualification program consists of two phases: Phase A, Design Proof Tests and Phase B, Mission Life Tests.

Design Proof Tests

Design proof testing includes the following tests:

Transportation and handling (including climatic environments)

Electromagnetic interference and explosion proof

Prelaunch dynamic environments (static firing)

Sequentially applied maximum expected mission environments. (These tests are performed to the specification limits and are designed to verify the ability of the product to withstand the maximum environmental and performance stresses expected during a mission.)

Off-Limit Tests

These are tests designed to verify environmental and functional design margins by testing a product beyond the specification requirements to failure. Specific test conditions are related to the failure modes having ramifications in crew safety and mission success. Stresses imposed (either functional or environmental) are those considered most likely to produce the failure defined as critical by the failure mode analysis.

Mission Life Tests

The Mission Life Tests (Phase B) consist of exposure of the equipment to single and combined natural environments, simulating the conditions expected during a lunar mission. The definition of a lunar mission includes all ground checkout time accumulated on each system in addition to the flight environments. The environments imposed are nominal values of those expected, in contrast to the peak values imposed during the design proof tests. The tests defined in this section will be performed on higher levels of equipment assembly than those defined in the design proof tests. Preferably, the entire subsystem will be subjected to these tests, although test facility limitations and the size of the various subsystems will govern the exact level of assembly that can be tested.

Each unit assigned to the life tests will be required to complete two mission sequences without failure, providing the second mission does not extend beyond the life of the equipment. Upon completion of the two mission sequences, critical and limited life items may be replaced and (as defined in the procurement specification) the equipment shall then be subjected to another dual mission simulation cycle, to assure repeatability of results.

TEST DATA EVALUATION

Data Analysis

The objective of the earliest testing of nonflight hardware is the elimination of weaknesses. This is the time when the greatest number of design changes are anticipated. Each malfunction that occurs during testing within specification limits will be the subject of a malfunction report and will be corrected to preclude recurrence. Although the action may involve design, fabrication, processes, methods, tools, or materials, it will be handled expeditiously to achieve rapid reliability improvement. All data accumulated from application approval testing will be statistically evaluated by design and reliability engineers assigned to the specific equipment being tested.

Testing will provide data necessary to determine functional compliance through analysis of variance and regression techniques and establishment of parameter trends. Figure 7-3 shows the relationship between data acquired by a typical test plan and the determination of the probability of out-of-tolerance operation. Component test data will yield mean functional parameters, the variation about the mean due to individual environmental stresses and their natural combinations, and certain differences between manufactured components. Similar values will also be determined for each system from part, component, and subsystem test results.

In Figure 7-3, "A" represents the specified design limits and "B" indicates the maximum allowable limits of the subsystem functional parameter as derived from subsystem and system off-limit design analysis and tests. Subsystems operating outside of "B" are those that will contribute to unreliable operation. Analysis can be made for all functional parameters in a similar manner. Subsystem reliability allocations limit the allowable frequency of off-limit operation and determine the tolerance variance distribution.

Extrapolation of test data will aid in establishing mean-time-to-failure, failure distribution, and functional parameter regression. Increasing environmental stress levels above specification limits will permit further correlation of failure distribution with environmental influences and demonstrate equipment design margins. These data will be used to define design deficiencies as unusual parametric drift trends on equipment. Evaluation of application approval data will provide a basis for establishing component and system parameter limits to be utilized during acceptance and prelaunch testing, review of specification requirements, and equipment reliability status audits.

FLIGHT HARDWARE TESTS

Reliability Measurement

Flight hardware test data will be processed and analyzed for quick reaction to malfunction data and for rapid assimilation of trend data. Malfunctions that occur or are discovered during the tests will receive top priority for corrective action. On-the-spot failure analyses will be extensively employed in these tests. Performance limits will be determined by design studies of system requirements and by tolerability and integration measurements. Operating parameters, measured as a function of time, will be utilized to define the traditional "go, no-go" acceptance criteria.

An example of the approach for establishing the criteria for measuring and analyzing trend data is shown in Figure 7-4. The qualification time includes all scheduled ground test time, maximum mission time (including prelaunch, launch and flight, reentry and recovery), and a safety margin. The safety margin is established for each item on the basis of the critical nature of the time-function relationship. Trend limits are established about this time base as a result of reliability analysis and the results of data from all applicable tests.

"Go" status is determined by analysis of performance measurements at preselected times during manufacturing and test operations. If the data indicate a trend as shown on the "go" line, a go status has been maintained and the required assurance of mission success is achieved. If performance exhibits regression as shown on the "no-go" lines, then mission requirements would not be satisfied or are doubtful of achievement.

These measurements, along with high-level inspection requirements for characteristics that cannot be measured during these tests, represent the evaluation tools for flight hardware. It can also be seen that when performance regression begins, a probable no-go can be determined prior to an actual out-of-limit conditions. Hardware can then be replaced on a preventive basis, rather than after a failure has occurred. Variations of this evaluation technique will be developed for off-on equipment where drift regression does not exist and for those equipment items where drift cannot be measured.

Test Milestones

Flight hardware test milestones are provided by the acceptance and prelaunch test phase of the over-all test program. These are associated with the equipment go status and provide A, B, and C control levels. (See Figure 7-4.)

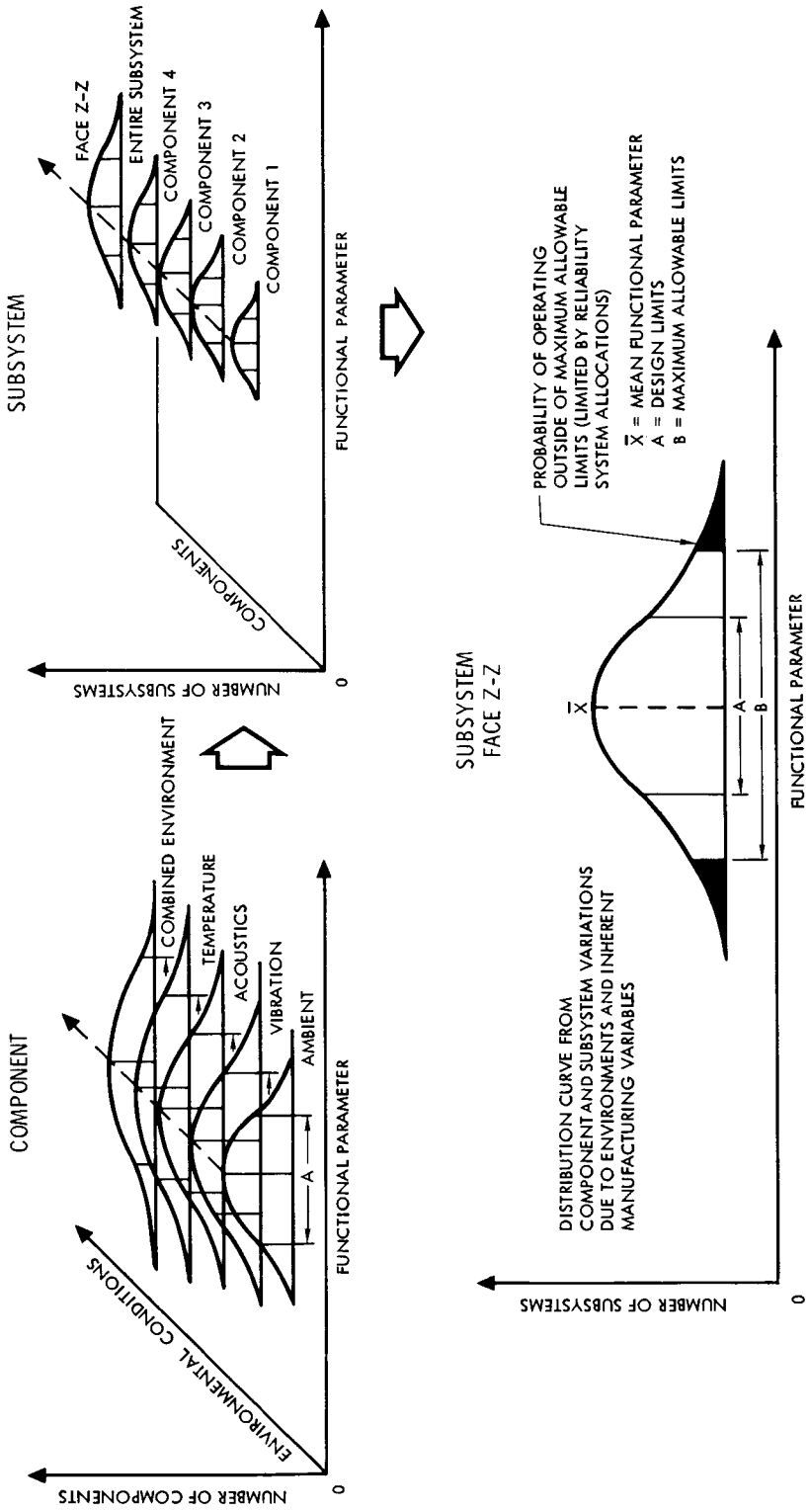
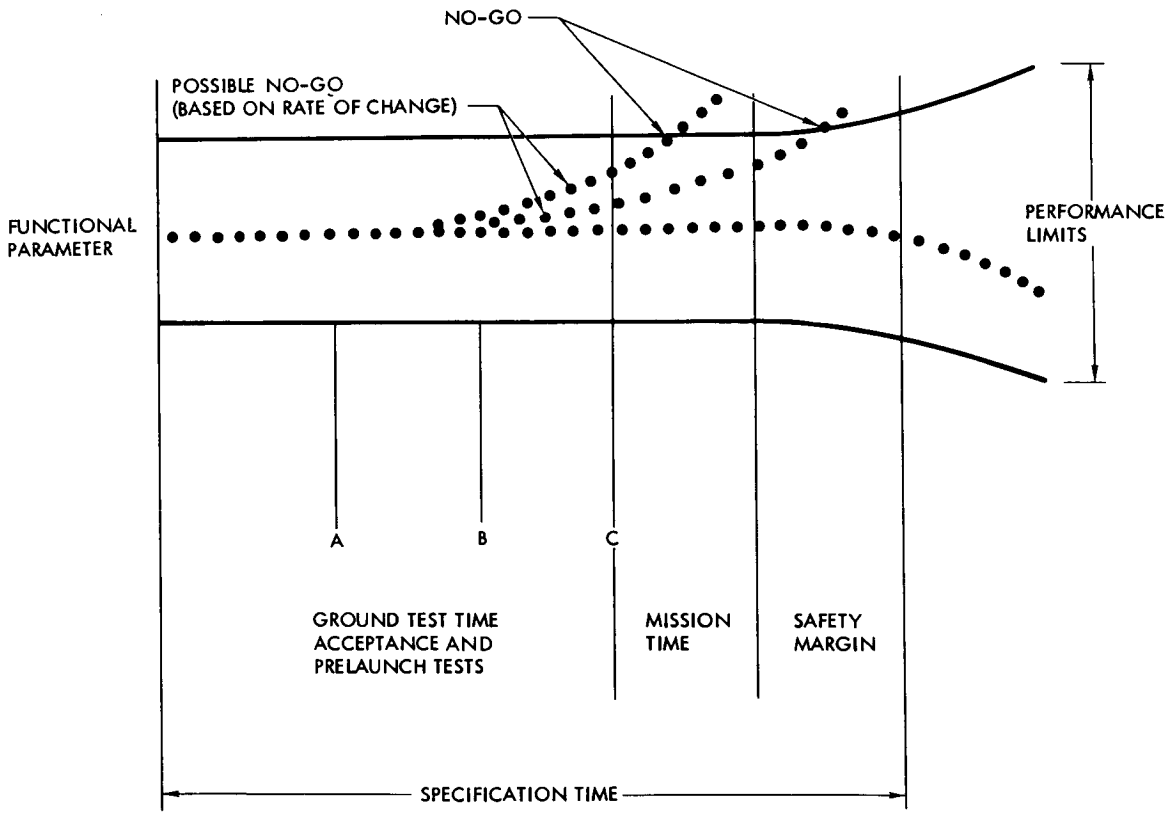


Figure 7-3. Typical Test Evaluation



ITEMS REMAINING WITHIN PERFORMANCE LIMITS AND WITH ACCEPTABLE TRENDS, THROUGH TIME:

A = COMPONENTS AND SUBSYSTEMS, GO (ACCEPTANCE)
B = SPACECRAFT, GO (PRELAUNCH OPERATIONS)
C = SPACECRAFT, GO (LAUNCH)

Figure 7-4. Flight Hardware Evaluation

Preliminary Assessment Approach

In the determination of reliability from assessment and projection analyses, the quality and quantity of data to be used will indicate the level of confidence that can be asserted for this early assessment approach. During the development phase of the program, test data consists primarily of supplier and subcontractor development, qualification and acceptance test phases and S&ID acceptance tests. The number of tests, test time and failure information are primary sources of data available for the preliminary analysis of reliability assessment status. A systematic screening procedure was established with design and reliability engineering concurrence in the determination of the suitability of approved data to be considered for assessment purposes.

Several methods are employed in the assessment of reliability. A nonparametric technique is used to estimate reliability of components, based upon the total number of tests conducted and failures observed, with 50 percent confidence. The exponential distribution is more appropriate when test time and associated failure data are available for assessing reliability. The reliability estimates are conducted on all levels of assembly and are combined with a mathematical model and logic diagram for the system examined. Integrated system reliability of the vehicle is estimated with the system serial rule. A similar approach is used to project reliability for additional ground checkouts that are conducted prior to launch. Projected reliability is an extension of assessed reliability to include the additional tests to be performed prior to launch of a vehicle with the assumption of zero failure criteria.

Predicted reliability may be used as a convenient base, or as an interval of comparison, to determine the relationship between an estimate that was derived from known failure data with mission operating times, and those derived from actual test of the equipment. This appraisal, however, results in an optimistic estimate of reliability. Assessed reliability is a pessimistic evaluation because it is based on limited data from tests of the item. The analytical method does not deal with the interaction or effects of failures upon other systems, and predicted values are used as best estimates when data is not available. Problems that occur are investigated to determine the nature of the failure, the possibility of this occurrence escaping detection during ground checkout, and the corrective action that must take place to ensure nonrecurrence. When major changes or redesign are a result of a problem, and a permanent fix is evident, then data accumulated beyond the change is employed in the calculation of reliability estimates.

The three reliability categories enumerated are considered to be most optimistic for predictions (based upon state-of-the-art information), pessimistic for assessments (based upon available test data), and pessimistic for

projections (based upon the assumption of success in all tests scheduled for completion by the launch date). They provide an excellent reference to customer and management to decide "go" or "no go" status at launch.

Control level A is assigned to an item when it has successfully completed in-process testing, source inspection at the supplier's facility, and all S&ID receiving inspection tests. Acceptance means that functional parameters have not drifted beyond the no-go limits designated in any of the test procedures. Control level B provides go status during combined systems operations in the factory prior to static firing. Throughout the manufacturing process, periodic functional measurments are required for most components of the spacecraft. These components and system parameters must remain within no-go limits established by the specification. Control level C is established by the static firing program and the final combined systems test prior to mating operations at the Florida facility. This control level establishes the final go status for spacecraft launch.

TEST FACILITIES

Commercial, supplier, government, and NAA test facilities will be used for Apollo qualification testing. Commercial and government test facilities may be utilized by the suppliers and S&ID when test equipment is not available internally or when test scheduling requires such action.

Approval and Standards

Commercial, government, and supplier test facilities must be approved by S&ID before utilization for the Apollo qualification test program. Each proposed test facility will be inspected by S&ID Apollo personnel. Laboratory and management personnel will be interviewed, and additional information will be secured through published material and correspondence. Approval will be contingent upon the appraisal of the following items.

Equipment and facilities
- Environmental simulation equipment (single and combined environmental capabilities)
- Measuring equipment
- Recording equipment
- Calibration equipment
- Standards laboratory
- Failure analysis equipment and facilities
- Photographic equipment
- Plans for new equipment
- Inspection facilities

Methods
- Methods, procedures, and standards documentation
- Housekeeping
- Data recording
- Reporting
- Personnel training
- Vended tests
- Test equipment calibration and certification

Personnel qualification
- Numbers and skills available
- Education
- General experience
- Military specification familiarity
- Statistical test experience
- Failure analysis experience

Management
- Organization
- Supervisory control
- Governmental agency resident representation
- Scheduling

NAA/NASA past experience with facility
- Prior surveys
- Certification record
- Past performance

All test facilities will be under continuous surveillance by S&ID representatives during Apollo qualification tests. Previously established standards must be maintained in order to retain approval status.

Rated Commercial Facilities

S&ID has conducted surveys and delineated qualified commercial test laboratories in the greater Los Angeles area. Table 7-1 presents the major areas of capability of each laboratory approved to date. All survey reports relating to the Apollo test program will be documented and reviewed periodically to include new laboratory capabilities and to reflect the latest surveillance information.

Table 7-1. S&ID Approved Test Laboratories and Capabilities

Laboratories	Mechanical	Electrical and Electronic	Combined Environments	Cryogenics	Pyrotechnics and Explosives	Random Vibration	Acoustical	Cine-Radiography	LO_2 Cleaning	Shock Specialization	GSE Testing
Action Laboratories*	X	X									
AMLAB*		X				X	X				X
Associated Testing Laboratories*	X	X					X				X
AVCO Corporation*	X	X	X			X	X				
Beech Aircraft Corporation	X	X		X		X					X
Belock*	X	X									
Boyle Engineering Laboratories											X
Component Evaluation Laboratories	X	X			X	X					X
Environ Laboratories	X	X				X					X
Gaynes Engineering Company	X										X
General Testing Laboratories	X	X				X					X
Inland Testing Laboratories	X	X									X
Janitrol Aero						X					X
New York Testing Laboratories, Inc.	X	X			X	X	X		X		X
North American Aviation, Inc.	X	X				X	X				
Rototest Laboratories	X	X				X	X				
Thiokol, Hunter-Bristol Div	X										
United States Testing Company	X	X	X	X		X	X				X
United Testing Laboratories	X	X	X	LN_2 only	X	X			X		X
Universal Research and Testing Labs											
Wyle Laboratories	X	X	X	X	X	X	X		X		X
York Research Corporation*	X	X					X				X

*Preliminary laboratories evaluation

VIII. NONCONFORMANCE REPORTING AND NONCONFORMANCE ANALYSIS

The Apollo requirements for crew safety and for flight success will necessitate planning, management, engineering, and, in many cases, product development that are orders of magnitude greater than those of present technology. To this end, a nonconformance reporting and a nonconformance analysis system has been established in all equipment areas, from the earliest feasible design evaluation phase through the complete mission of Apollo. This system will encompass both spaceborne and ground support equipment.

The basic concept underlying the nonconformance reporting system for the Apollo is found in Paragraph 3.1(h) of specification MIL-R-27542, which states:

> The collection, analysis, and feedback of information to the proper action activity with appropriate follow-up are fundamental to accomplishment of mature design.

SYSTEM DESCRIPTION

Objectives

The Apollo nonconformance system has as its objectives the recording, collecting and analyzing of data, the ensuring of corrective action, follow-up and feedback on failures or problems occurring at the following locations:

- Major subcontractors
- Vendors and suppliers
- In-plant design evaluation, fabrication, installation, test, and checkout
- Customer-controlled tests and checkout
- Off-site installation test and checkout
- Customer use on the mission

Also, the system provides for the recording, collecting, analyzing, and feedback of all other significant reliability data, such as operating time, cycles, replacement information, maintenance activities, adequacy of checkout equipment, configurations involved, and MRB action.

Requirements

Nonconformance analysis will determine the failure mode, probable cause, and failure effects and differentiate between failures due to inadequate equipment design, and those attributable to human error in fabricating, assembling, handling, transporting, storing, maintaining, and operating equipment. On-the-spot failure diagnoses will be accomplished by a team of engineering specialists, reliability engineers, and quality control engineers; and reasonable facilities will be readily available so that the program can continue without interruption while analysis is being accomplished. The method of analysis and reporting will be compatible with the NASA reporting system. Nonconformance data flow is indicated in Figure 8-1.

Nonconformance and failure data will be fed back and used for corrective action as early as possible in the design phase. Therefore, the results of analyses will be transmitted to the appropriate design, control, or production activities with priority and provisions for remedial engineering and/or manufacturing actions to prevent nonconformance and/or failure recurrence.

Definitions

Nonconformance: that which does not comply with the requirements of applicable drawings, specifications, or procedures. May be a discrepancy or a failure.

Discrepancy: any nonconformance to drawing, specification, or good quality practice. A failure may result from a discrepancy.

Failure: the cessation of ability of an item to meet the minimum specified performance.

Report Descriptions

Failure Reporting (Nonconformance Report, NCR)

Nonconformance and/or failure reporting describes the symptoms at the time of failure, identifies the items involved, describes incidents leading to the failure, and documents the disposition of the hardware. In addition, it describes rework, replacement and analysis required if the nonconforming hardware can be immediately made to conform with the criteria. Figure 8-2 illustrates the NCR form.

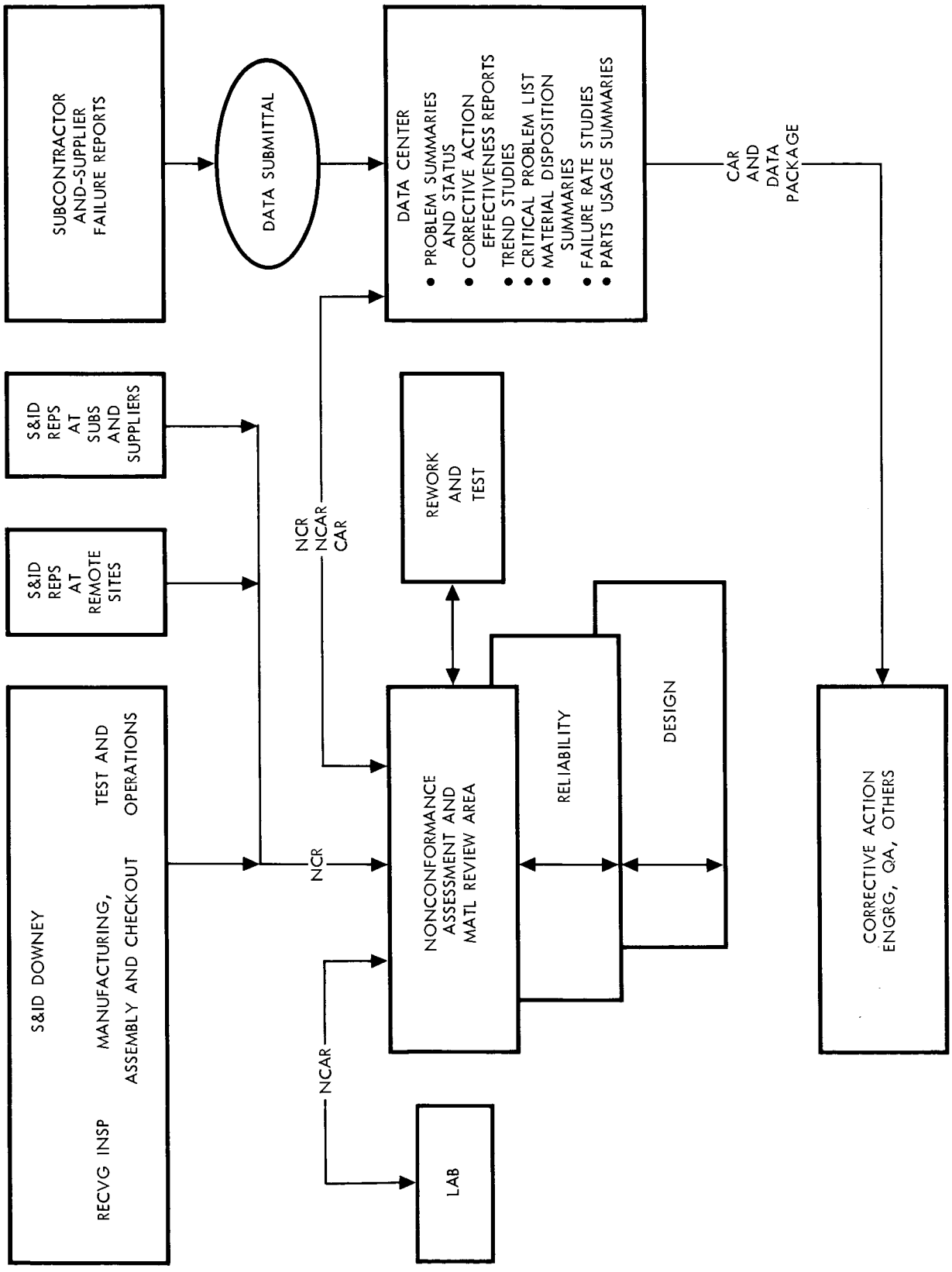


Figure 8-1. Nonconformance Data Flow

Failure Analysis and Corrective Action (Nonconformance Analysis Report, NCAR)

An NCAR form is initiated when an S&ID diagnostic teardown is required to determine the cause of failure. Instructions and the extent of teardown are entered on the form and, subsequently, the result of the teardown analysis. When significant corrective action is necessary, a statement of the action required, those responsible for action and, subsequently, the action taken are entered on the NCAR form. Figure 8-3 illustrates the NCAR form.

Supplier Failure Analysis Report (Form 925-R)

A 925-R form is initiated when supplier diagnostic teardown is required to determine the cause of failure of equipment malfunctioning while under S&ID cognizance. A symptomatic description of the malfunction is entered on the form and forwarded to the supplier with the malfunctioned hardware. The results of the teardown analysis, including a description of the failure evidence, cause of failure and corrective action taken are entered by the supplier and returned to S&ID for evaluation and action. Figure 8-4 illustrates the 925-R form.

Time Limitations

Nonconformance and failure reports are prepared by Quality Control or Reliability personnel as soon as the problem is encountered. Nonconformance or failure reports issued from S&ID in-plant areas will be transmitted to the data center within 24 hours after the occurrence. Those initiated at remote sites will be received by the data center within 3 days from date of issue. Copies of all failure reports will be maintained by S&ID Data Control Center and will be available to NASA-MSC upon request. Included in these reports will be information required to identify the item, circumstances at the time of occurrence, and symptoms observed.

Rework, replacement, and analysis sections of the nonconformance report (NCR) will be completed and returned to the data center within 10 days of the receipt of the failed article. Where corrective action is required to bring the failed articles into conformance with the criteria, the complete report, containing corrective action taken, will be returned to the data center within 10 days after the failed article is received. These reports will also be available to NASA-MSC upon request.

Diagnostic teardowns of failed articles will be accomplished within 10 days after initiation of the nonconformance analysis report (NCAR). Generally, corrective action implementation will be accomplished within 15 days after initiation of an NCAR requiring corrective action. Corrective action that requires NASA approval and/or negotiations may extend the 15-day requirement. Effectivity dates on the latter will be determined on an individual basis for each such case.

CLOSED-LOOP SYSTEM

A closed-loop failure reporting, analysis, and feedback system will be established for parts, components, and equipments during design, development, test, fabrication, installation, and checkout. All items of spaceborne equipment for all program phases that are directly associated with crew safety or flight success will be included, as well as selected items of GOSS where it is known that the item does not have the design or achievable reliability to support all program phases and where new items of equipment are required to support various program phases. GFE, Associate Contractor equipment and selected items of ground support equipment that must meet assigned reliability requirements will also be included in this reporting system.

Problem and failure reporting and corresponding corrective action for Apollo will be accomplished by using procedures and forms that have been developed. (See Figures 8-2, 8-3 and 8-4.) The basic philosophy will be to search out problem areas and solutions and to prevent failures from occurring.

Essential to the failure reporting system are the reliability engineers who are responsible for the analysis of each failure. The reliability engineer is also responsible to follow up each failure to assure that corrective action has been implemented and the problem resolved. Diagnostic teams of specialists will support the reliability engineers in the analysis of problems or specific failures. An urgency category will be established, assuring immediate action on problems affecting personnel or crew safety or accomplishment of mission objectives.

Procedures for the reporting system, Policy J-403 and QAOP M1-2.2.1, are in use. They utilize failure report formats compatible with program requirements and mechanized data processing.

Sufficient laboratory facilities are available to perform failure analyses on an urgent, high-priority, regular, and detailed study basis. An analysis facility will be located within reasonable distance from the work area (including field sites), and, if crew safety is compromised by a failure, assistance will be quickly available from any area.

Personnel within the central data processing area will process the reports, and a history retention status and follow-up file will be maintained. Periodic reports will be made to functional management and supervision defining the modes of failure demonstrated by the equipment, frequency of occurrence, corrective action being taken, and an estimate of the measure of effectiveness of the corrective action.

Failures experienced during test and ground operations will be interpreted in terms of influences on mission success or crew safety had they occurred in flight. Best engineering judgment will be employed in evaluating the latter incidents.

The discrete level at which failure can be localized (e. g., material, part, component, subsystem, or system) will be established and the cause of failure identified. Possible failure causes include design, workmanship, human error, procedures or documents, contamination, inadequate maintenance, and wearout.

All symptomatic failures will be analyzed and verified. Those failures that cannot be verified will be given special attention to determine the reasons for the failure symptoms and adequacy of detection and isolation equipment. The failure mode, the effect of the failure, and the priority of the resolutions will be established. The action agency for further study or resolution will be identified and a tentative approach to the solution suggested.

Feedback

Feedback includes the corrective or preventive action accomplished or required, as follows:

Permanent solution to the problem, including documentation of the implementing instrument
Temporary fix
Spares provisioning
Repair kits
Revised test procedures or other documents
Proper training in the use of the equipment
Other actions as appropriate to the cause of failure

NASA Unsatisfactory Reports and Discrepancy Reports

A procedure is under development for negotiation with the NASA to provide for processing of NASA originated Unsatisfactory Reports (UR). The procedure proposes to process UR's by using existing UCR System controls and facilities.

Discrepancy Reports (DR) are reviewed, summarized and evaluated for Reliability significance. Related DR's and NCR's are referenced in the Monthly Failure Summary.

Monthly Failure Summary

A monthly failure summary, S&ID 62-822, listing significant failures occurring at S&ID and Subcontractor/Supplier facilities, is regularly submitted to the NASA. The summary identifies hardware by subsystem, and notes a description of the failure, the corresponding failure analysis and its corrective action. Follow-up is made to assure closed loop response on all items reported.

Failure Notification of Explosive Devices

The NASA is notified, within 24 hours of occurrence, of all explosive device failures. A division procedure, J-403, is in effect which directs immediate notification be forwarded by Program Design Engineering.

NORTH AMERICAN AVIATION, INC.
SPACE and INFORMATION SYSTEMS DIVISION

NONCONFORMANCE REPORT
(NCR)

1 TYPE OF NC. ☐ FAILURE ☐ DISCREPANCY ☐ UNSATISFACTORY ☐ OTHER

2 REPORT NO. M 01851 | 3 DATE MO. DAY YR. | 4 INITIAL REPORT NO. | 5 PROJECT

6 ITEM IDENTIFICATION & OPERATIONAL USAGE

	NAME	PART NO.	SERIAL/LOT/HEAT NO.	HOURS-MINUTES-SECONDS-CALENDAR-CYCLES-MILES WHEN RMVD	WHEN INSTLD	NET USAGE	TYPE
NC ITEM							
NEXT ASSY							
SYSTEM							

END ITEM MODEL NO.	END ITEM SERIAL NO.	ITEM REF. DESIG.	MFGR NAME (NC ITEM)	SUPPLIER NAME (NC ITEM)
REPLACEMENT PART NO.	REPLACEMENT SERIAL NO.	MAT. INSP. & REC. (DD250)	PRR/RR/FAIR NO.	QTY OF ITEM UNIT OF MEAS
GENERAL ORDER NO.	RELEASE NO.	PURCHASE ORDER NO.	ASSC CONTR RPT NO.	CUST REPORT NO.

7 NONCONFORMANCE/OPERATION DATA

REFERENCE DOCUMENTS	PARA NO.	REV DATE	YES ☐ NO ☐ NAME	DEPT & PHONE NO.
TEST NO.	FACILITY	LOCATION / DEPT	ANAL ASSIGNED TO	REF ANAL DOCUMENT
GSE MODEL NO.	GSE SERIAL NO.	OCCURRED DURING	DATE: MO. DAY YR. / RETEST OK ☐ YES ☐ NO	925-R REQUIRED YES ☐ NO ☐

8 MATERIAL REVIEW BOARD DISPOSITION

QUALITY ENGINEER	SUP INFO REQ NO.	DISP	YES ☐ NO ☐ NAME	DEPT & PHONE NO.	
DISP TYPE	23H-1 NO.	STANDARD REPAIR NO.	DATE: MO. DAY YR.	CORRECTIVE ACTION ASGD TO DEPT	DATE: MO. DAY YR.

9 ANALYSIS REQUIREMENT

10 CORRECTIVE ACTION REQUIREMENT

11 DESCRIPTION OF NONCONFORMANCE

NAME | DEPT & PHONE NO.

12 MATERIAL REVIEW BOARD DISPOSITION

INSP. ACCEPT. DATE

13 QUALITY CONTROL | 14 ENGINEERING | 15 CUSTOMER

16 IMMEDIATE CORRECTIVE ACTION STATEMENT

SIGNATURE

17 DIST DATE INITIAL REPORT YR MO DY | 18 DIST DATE UP-DATED REPORT YR MO DY | 19 DIST DATE FINAL REPORT YR MO DY

FORM 963-M (REV. 10-62)

PAGE _____ OF _____

Figure 8-2. Sample Nonconformance Report (Sheet 1 of 2)

NORTH AMERICAN AVIATION, INC.
SPACE and INFORMATION SYSTEMS DIVISION

NCR NO. _____

NONCONFORMANCE REPORT CONTINUATION SHEET

11 DESCRIPTION OF NONCONFORMANCE (CONT'D)

12 MATERIAL REVIEW BOARD DISPOSITION (CONT'D)

FORM 963-M-1 (REV. 10-62)

PAGE _____ OF _____

Figure 8-2. Sample Nonconformance Report (Sheet 2 of 2)

NORTH AMERICAN AVIATION, INC.
SPACE and INFORMATION SYSTEMS DIVISION

NONCONFORMANCE ANALYSIS REPORT

(NCAR)

1 NCR NO.

NCR BY _____ LOCATION _____

2 IDENTIFICATION

NAME	PART NO.	SERIAL/LOT/HEAT NO.	NAME OF MANUFACTURER
NC ITEM			
NEXT ASSEMBLY			
END ITEM			

3 CORRECTIVE ACTION ASSIGNMENT

INFORMATION ONLY	ASSIGNED TO	DATE SUBMITTED	DATE DUE	REFERENCE REPORT	DSC NO.

ORIGINATED BY DEPARTMENT	NAME	LOCATION	PHONE

4 DESCRIPTION OF NONCONFORMANCE & HISTORY 5 ANALYSIS 6 CONCLUSION AND/OR CORRECTIVE ACTION RECOMMENDATIONS
7 ACTION TAKEN (USE SPACE AS NECESSARY FOR THESE ITEMS. GIVE ITEM NO., THEN STATEMENT).

8 CORRECTIVE ACTION BY

NAME	PHONE	DEPT & GROUP	DATE	SUPERVISOR

FORM 963-M-2 (REV. 10-62)

FINAL DISTRIBUTION DATE

Figure 8-3. Sample Nonconformance Analysis Report

NORTH AMERICAN AVIATION, INC.
SPACE and INFORMATION SYSTEMS DIVISION

SUPPLIER FAILURE ANALYSIS REPORT

N. A. A. PART NO.	SUPPLIER		DATE OF FAILURE
PART NAME		SERIAL NO.	N. A. A. FAILURE REPORT
SUPPLIER PART NO.	OPERATING TIME	RELIABILITY ANALYST	APPROVED BY	P. R. R. NO.

TROUBLE

TROUBLE EXPERIENCED DURING: CHECKOUT ☐ OPERATIONAL { START ☐ RUN ☐ }

FUNCTIONING AS UNIT ☐ ASSEMBLY ☐ SYSTEM IN { TEST ☐ MISSILE ☐ }

TO BE COMPLETED BY SUPPLIER

DESCRIPTION OF FAILURE EVIDENCE FROM TEAR DOWN AND/OR FUNCTIONAL CHECK

ANALYST TITLE DATE

CAUSE OF FAILURE: INCLUDING MODE AND FAILED COMPONENT NAME, NUMBER, SUPPLIER

ANALYST TITLE DATE

CORRECTIVE ACTION BY SUPPLIER INCLUDING EFFECTIVITY DATE OR SERIAL NO.

ENGINEER TITLE DATE

DATE RETURNED TO N. A. A.	COMMENTS ON CORRECTIVE ACTION	RELIABILITY ANALYST	DISPOSITION OF THIS REPORT

FORM 925-R (REV. 9-62)

N. A. A. FILE COPY (Retain until NAA copy is returned)

Figure 8-4. Supplier Failure Analysis Report

IX. MANUFACTURING RELIABILITY

Responsibility for maintaining design reliability in the physical product rests with Quality Control and Manufacturing. Failure of equipment in service due to errors in purchasing, packaging, handling, workmanship, and inspection are as important as failures due to design. The Apollo reliability/crew safety requirements necessitate a stringent manufacturing control program. To accomplish this, a quality assurance program integrating Reliability Engineering, Quality Engineering, and Quality Control has been designed to assure that the quality requirements are determined and satisfied throughout all phases of contract performance. The manufacturing reliability program will provide for monitoring, control, and improvement of manufacturing processes and education, motivation and certification of personnel to assure that the reliability requirements are satisfied.

This manufacturing reliability program relies on (1) assessment of design, manufacturing, and inspection capabilities, (2) documented control of procurement, manufacturing, and inspection, (3) reporting and analysis of discrepancies and malfunctions, and (4) a method for recurrence prevention. Cognizance is given to the preparation, utilization, and retention of documents and to the methods for interdepartmental resolution of manufacturing reliability problems.

Assurance of an effective control system is demonstrated in the following manner:

1. Process capability is measured and compared with applicable specifications.

2. Statistical tools are employed to treat failure and discrepancy data to determine actual conditions and predict future reliability trends.

3. Performance and yield charts are established to provide data for corrective action and subsequent measures of effectiveness.

4. Product improvement is accomplished by utilizing design and reliability reviews, expected and actual fraction defective of a product, correlation of discrepancy and failure data, and effective measures to prevent recurrence of a discrepancy or failure.

The detailed organization, methods, and procedures for accomplishing the objectives of the manufacturing reliability program are defined in the Apollo Quality Control Program Plan (SID 62-154). Included in this plan is the identification and traceability system that will be used for all Apollo hardware.

This document and SID 62-154 are considered as supplemental reports, fulfilling contractual requirements and defining S&ID's total quality and reliability assurance program.

X. RELIABILITY INDOCTRINATION AND TRAINING

A continuous reliability-oriented training program is maintained for all personnel connected with the Apollo project. It is recognized that the reliability of any product can only result from an integrated team effort in all phases of the program, from design conception to delivery of the finished product. This philosophy has resulted in considerable importance being placed on the reliability training, indoctrination, and motivation of all personnel from top management, staff areas, and line functions. The effort includes the specialized training and/or capability certification that will be given all Apollo personnel whose work has any influence on product quality and reliability.

A high ratio of contribution to cost in indoctrination and training activities is essential. Each part of the program outlined here has been carefully analyzed as to need and mode of operation. Controlled experiments have been conducted in some cases to assure that only those activities that can maintain a high ratio are implemented.

All Apollo personnel are selected and assigned tasks on the basis of past experience, education, cooperation, attitude, adaptability to reliability concepts, and awareness of the importance of their tasks. Personnel applying for work in critical areas, regardless of position, are thoroughly investigated in matters pertaining to their particular field. Indoctrination, training, and continued evaluation are an integral part of the Apollo Program, to ensure proficiency, proper motivation, and incentive for achieving the desired goals. The S&ID Training Department, in coordination with the Apollo Reliability Manager and the various functional departments, is responsible for in-house and subcontractor reliability indoctrination, motivation, and training. Reliability indoctrination is included in other S&ID training programs whenever the subject provides a suitable means for reliability motivation or education.

TRAINING

All newly employed personnel receive a general indoctrination lecture that explains company policies, divisional programs, and available in-house facilities. In addition, new employees who will be associated in any way with the Apollo Program receive at least 2 hours of orientation on reliability concepts as applied to Apollo. They are briefed on the importance of space exploration, the reality and the mission of Apollo, NASA's and NAA's roles in space programs, and the requirements for reliability and crew safety. Appropriate motion pictures are employed to supplement lecture material.

Management

Courses on the reliability program and qualification test plans, reliability concepts, and analytical tools are available to all supervisory and management personnel. Appropriate news releases, reliability articles, and industrial psychology data are distributed to management as a means of providing continuing awareness of their assigned task. Management also participates in weekly technical discussions with engineering, reliability, and quality control personnel and in monthly technical meeting with subcontractors to provide direction.

Supervision

Supervisory personnel receive courses in the reliability program plan, the Apollo test plan, job instruction training techniques, familiarization in engineering methods in applicable fields, reliability data analysis and interpretation, quality control methods, methods of constructing yield charts, and personnel evaluation sheets as related to Apollo. Members of supervision also attend periodic reliability seminars. Interdepartmental reliability improvement meetings covering production problems relating to design are also attended by supervision and responsible engineers. Refresher and more advanced training programs are given to members of supervision at regular intervals. Upon recommendation from the Reliability or Training Department, supervisory personnel are retrained after a prolonged absence, when a loss of proficiency is noted, or when new subject matter is introduced.

Engineering

All engineers on the Apollo program receive reliability training and are indoctrinated in the influence of their decisions on reliability and crew safety. Formal courses are offered covering the various technical aspects of reliability, statistical reliability theory, systems and component analysis, failure allocations, test planning and analysis, data requirements, and methods of data analysis. The necessary information to enhance discussion of specific problems encountered in achieving the desired product reliability are developed and presented.

Production

All Apollo production personnel receive special training in their related fields. Production, inspection, and test personnel are given specialized training in quality and reliability standards. Actual operating conditions are simulated for greater effectiveness in training. Special measuring techniques and devices are used to assure capability and

proficiency. Personnel performing critical visual operations are subjected to various eye tests, such as binocular vision and astigmatism. Personnel performing critical precision operations are tested for manual dexterity, where applicable.

In special skill, equipment, and process categories, certification is employed in accordance with the provisions specified in the Apollo Quality Control Program Plan (SID 62-154). Certification of special processes, fabrication and inspection operations (such as welding, soldering, wiring, radiography, magnetic particle, dye penetrant, and bonding) may be reviewed or repeated by NASA to verify the proficiency for retention of such certification. Personnel who satisfactorily complete training and the required tests are given material evidence of certification, which they are asked to carry on their person while performing such duties. Records indicating the date of last certification are maintained. The period of effectivity for all certifications is specified, and the individual is recertified at the end of the established period.

Individuals transferred to a new operation are subject to recertification. Retraining and recertification may also be necessary upon recommendation of the Reliability, Quality Control, or Training Department. The latter is initiated by prolonged absence, evidence of loss of proficiency, or a change in production procedures regardless of established certification periods.

Particular attention is paid to the indoctrination and skill of inspectors, since the final checkout of their particular product is of primary importance. Special training procedures have been established to measure the effectiveness of the inspector training program (e.g., samples with known imperfections are submitted to inspectors to ascertain their knowledge of the product and acceptance criteria).

Utility and Clerical

Clerical personnel are taught the importance of accuracy in documentation and other significant functions. Utility personnel are made aware of the importance of their contribution to the Apollo effort, with emphasis on the specific tasks to which they are assigned.

TRAINING AIDS AND SUBJECTS

The meaning of reliability is continuously conveyed to all management, supervision, and engineering personnel by such training aids as motion pictures, closed-circuit television, slides, and sound tape.

Cutaway models, three-dimensional mock-ups, and other beneficial aids are used to facilitate instruction. A special illustration group assists in the production of posters, artwork, animation, and photographic aids.

Production personnel are provided with operational instruction sheets on all manufacturing operations, production instruction sheets, and pamphlets which explain in detail each operation. These are revised to reflect current information. Motion pictures and closed-circuit television are used for instruction and demonstration where advantageous. Slides and sound tapes demonstrate right and wrong production methods. In critical cases, slow-motion pictures, augmented with three-dimensional cutaway models, are used.

Closed-Circuit TV Indoctrination Series

Extensive use of closed-circuit television (CCTV) is made to provide management, supervisory, and engineering personnel on the Apollo Program with the principles and methods of reliability. The CCTV indoctrination series includes the following examples, each of 30-minutes duration.

1. Apollo Reliability Program Plan
2. Design Review
3. Systems Design Analysis
4. Qualification Test Plan
5. High Reliability Parts Control
6. Identification and Traceability
7. Others

Closed-Circuit TV Motivational Series

All employees on the Apollo Program whose work relates to the quality and/or reliability of the product attend CCTV motivational showings. The approach builds a strong association between the employees' basic needs and the attitudes and response patterns that are required. In order to accomplish this, the training is presented to the personnel within a familiar framework of skills and information. The CCTV motivational series includes the following examples, each of 20-minutes duration.

1. Top Management Speaks on Product Assurance
2. Why the Space Program is Necessary
3. 100,000 Astronauts—the Aerospace Employees
4. The Apollo Mission
5. Mechanical Excellence in Manufacturing
6. The Importance of Cleanliness in Manufacturing
7. Others

Closed-Circuit TV Subcontractor and Supplier Series

Suppliers and subcontractors on the Apollo Program participate in the CCTV motivation series. In addition, a series of indoctrination programs of special interest to the supplier and subcontractor are made available. The following are examples of video tapes and films provided for supplier and subcontractor use.

1. Supporting the Apollo Reliability Program Plan
2. Supporting the Apollo Qualification Test Plan
3. Apollo Procurement Documents

Course Subjects

Initial subject matter to be covered by formal courses include the following, in order of planned presentation:

Fundamentals of reliability mathematics
High-reliability parts
Reliability program plan
Systems analysis techniques
Computer methods of design analysis
Symbolic logic in reliability
Subcontractor and supplier reliability training
Reliability aspects of procurement
Reliability prediction and assessment
Qualification test plan

Course descriptions have been, or will be, prepared on each of these courses. A sample description of a current program is given in Figure 10-1. Other courses will be added as the program progresses.

Technical Publications

The Apollo engineer has available to him various original technical publications that are prepared to upgrade technical competence in the reliability area. A sample listing of these publications is as follows:

1. Reliability Techniques
2. Reliability Definitions
3. Fundamentals of Reliability Mathematics
4. Design Analysis Techniques (three volumes)
5. Computer Methods of Analysis
6. Reliability Apportionment and Assessment
7. Design of Qualification Tests
8. Others

MOTIVATION

Every attempt to motivate Apollo personnel is being made. Posters and slogans are displayed in prominent places and changed weekly. Pride of association is stimulated by imprinting "Apollo" on badges of personnel assigned to the project. Display boards, the S&ID newspaper, and periodic home mailings are used to maximum advantage to inform employees and their families of Apollo status. News clippings and other related information are posted.

Credit, rather than censure, for recognition of discrepant parts is extended to production personnel to increase product reliability and personal motivation. High-quality work is rewarded by recognition and publicity. Top management personnel appear frequently in Apollo areas, thus indicating a high degree of personal interest in the personnel and program progress. The S&ID suggestion system is exercised to the utmost.

SUBJECT: Computer Methods of Electronic Design Analysis

A. Course Objectives

The objectives of this course are to give design, electrical, electronic, and reliability engineers at S&ID various advanced methods of analysis that have been developed and a working knowledge of the computer methods associated with each. This course is designed to acquaint the engineer with methods of writing circuit equations in a form which can be easily programmed and to interpret the information obtained from the computer.

The Minuteman computer methods of circuit analysis developed at Autonetics will be described. A sample circuit will be used to compare the various computer methods of circuit analysis.

B. Attendance Details

Number of Sessions	Approximately 30
Duration of Each Session	1-1/2 Hours
Starting Date	16 April 1962
Time	9:00 to 10:30 AM Monday and Wednesday
Location	Training Room 8 (N20-E26)

C. Course Content

The following analytical methods will be considered in detail during this lecture series:

1. Monte Carlo Techniques
2. VINIL Method
3. Moment Method
4. Parameter Variation Method
5. Mandex Worst-Case Analysis

Topics to be covered include:

1. Basic network topology
2. Loop current equations
3. Node voltage equations
4. Steady-state analysis
5. LaPlace transforms
6. Circuit transformations
7. Network functions, driving point, and transfer
8. Network response
9. Equivalent circuits

D. Prerequisites

Because of the advanced mathematical nature of certain of the subject matter, personnel with the required academic training will gain the most from the course. This should not discourage attendance by all interested personnel.

Figure 10-1. Apollo Reliability Training Course Description

FEEDBACK

All responsible design, reliability, and quality control engineers are trained in the interpretation of failure feedback information and its use in formulating corrective action. All applicable production and field personnel receive extensive training in the identification and proper recording of failures in order to simplify interpretation and recognition of failure modes. The importance of accurate and clear documentation with respect to failure evaluation and the effectiveness of corrective action are emphasized.

SUPPLIER INDOCTRINATION

All subcontractors and suppliers are briefed on Apollo reliability and safety requirements and the latest methods of reliability enhancement and achievement, with particular emphasis on the critical nature of manned spacecraft. Each supplier or subcontractor is required by contract or purchase order to establish and maintain a reliability training program similar to that just outlined for S&ID. Reliability brochures and movies are distributed and shown to subcontractor management, staff, and line personnel.

Frequently, a group of suppliers is brought together for a supplier symposium that deals with matters of special interest to the group. When necessary, supplier symposia are conducted in various fields of specialization, such as metallurgy, manufacturing processes, and inspection techniques, in addition to such product areas as instruments, raw material, and high-performance electronic and electromechanical parts. During the course of these symposia, briefings are held on the importance of training in failure analysis, feedback techniques, and corrective action.

XI. HUMAN ENGINEERING

For those aspects of human engineering that bear directly or indirectly upon reliability, the appropriate design, test, and reliability groups will be supported by Life Systems personnel. This human engineering effort is described in the following paragraphs.

RELIABILITY PROGRAM SUPPORT

Reliability Formulation and Apportionment

A detailed analysis of typical Apollo missions and a description of all tasks in which Apollo crew members might participate are fundamental to a definition of the contributions of the crew to system reliability. The performance characteristics and limitations of crew members will be considered during reliability apportionment as an element in system reliability to the extent that primary or backup responsibility is assigned to them. Human engineering studies will be performed to support the requirements for data on human performance. These studies may include experiments, as well as surveys of data from appropriate earlier programs.

Reliability Design and Assurance

Task Analyses

At each stage in the design of the Apollo system, task analyses will be required to the most detailed level permitted by the design decisions already made or being considered. In early stages of design, function allocations will be made between crew and equipment and among crew stations. The allocations will be based upon quantitative estimates of accuracy and reliability of performance and will be made jointly with design and reliability engineers.

Human engineering analyses will be conducted to assure that all potential sources of human error are minimized in the spacecraft, ground support equipment, and associated ground operations through appropriate task assignments. Life Systems personnel will assist in man-machine trade-offs to ensure that optimum use is made of the crew members as power sources, controllers, pattern recognizers, and error detectors. This will permit simplification of certain vehicle systems whenever reliability can thereby be increased.

In later design stages, detailed task analyses will be made as a basis for specification of the precise characteristics and location of displays, controls, maintenance checkpoints, handling gear, and attach fittings. Where potential reliability problems are uncovered by the task analyses, experimental studies will be made to determine appropriate courses of action.

Experiments and Data Collection

Human engineering experimentation and the collection of relevant data from existing experimental literature will be continuing tasks. Wherever the characteristics of flight or ground crew members can affect the speed, accuracy, or certainty of system function, those characteristics will be of interest to the reliability program.

The operation, checkout, and maintenance philosophies embodied in preliminary designs and specifications for the Apollo vehicle, GOSS, ground support equipment, and GSE/vehicle interface will be checked for reliability functions against existing knowledge of performance of personnel on comparable programs, and for reliability functions. The performance that can be expected of crew members in the spacecraft environment will be described quantitatively to permit the estimation of the man-system reliability, to establish criteria for designing the crew into the system, and to formulate criteria for spares, space tools, and redundancy in equipment and procedures. Experimental studies will be performed, as required, to supplement existing performance data.

Experimental evaluations of alternate display, control, maintenance, and life support equipments will be performed to assure that the components and designs selected are compatible with overall reliability requirements, when operated by typical crew members.

Design Reviews

Human engineering personnel will participate in all design reviews. Conformity to SID 62-167, "Human Engineering Criteria for Space Systems," is a requirement for all Apollo designs, and continuous analysis and close coordination with design and reliability personnel will assure this conformance.

Program Review and Monitoring

The Life Systems Department will participate in reliability program reviews and will have a significant "voice" in areas involving man-machine relationships and crew safety. In addition, Life Systems will prepare appropriate sections of reliability progress reports.

RELIABILITY ASSESSMENT

Assessment Models

Life Systems personnel will participate with test and reliability engineers in the design of models for assessing reliability from tests presently planned, wherever human performance contributes in any way to the results. Detailed plans for human factors tests are included in the Apollo test plan.

The design of models to assess system reliability must take careful account of uncontrollable sources of variation in system performance. Variations in personnel and interaction effects involving personnel will be important sources of variance in some demonstrations. Compensating approaches and criteria for selection of operators will be planned in advance of any testing or data collection.

The materials and procedures for gathering system performance data will be designed and evaluated in advance of qualification testing. Experimental psychologists from the Life Systems organization will assist in the design and evaluation of test report forms, test procedures, and instrumentation related to crew member actions.

Demonstration Execution and Interpretation

Many subsystem tests will involve operators and maintenance personnel. Life Systems personnel, trained in the conduct of experiments involving personnel, will assist in the execution of these demonstration tests.

Control of the conditions under which personnel perform in subsystem tests will be essential to the collection of meaningful data. Life Systems personnel will describe the necessary controls and monitor the tests to see that the conditions are met. Collection of subsystem reliability data will, in some cases, involve the observation of operators by Life Systems personnel trained in the required control techniques.

Life Systems personnel will also participate in the analysis, interpretation, and reporting of tests intended to provide reliability assessment data.

FAILURE REPORTING, ANALYSIS, AND FEEDBACK

A substantial portion of the failures that may occur in fabrication, testing, handling, or use of Apollo equipment can be expected to involve human factors. Life Systems personnel will actively participate in failure reporting analysis.

Failure reports with human ramifications will be routed to and analyzed by Life Systems personnel so that human errors can be isolated and evaluated and corrective action taken. When a failure involving a human action is detected, Life Systems personnel will study the procedures and equipment involved in an effort to isolate the source of the failure and preclude recurrence. If necessary, direct observations will be made to confirm the failure mode and cause and to permit recurrence control.

MANUFACTURING ASSURANCE

Life Systems personnel will work with Quality Control, Reliability, Plant Engineering, and Manufacturing Planning in the development of techniques and equipment that will minimize opportunities for compromise of crew safety or equipment reliability through human error in the manufacturing process.

Manufacturing equipment and layouts will be subjected to an analysis similar to that conducted on deliverable maintenance or test equipment. Recommendations will be formulated and transmitted to appropriate design functions. Manufacturing, inspection, and handling procedures will be analyzed with the aim of reducing opportunities for component degradation or erroneous assembly. Written procedures for fabrication, assembly, inspection, and handling operations will be prepared.

Failures involving human elements during manufacturing or in-plant handling will be investigated in much the same way as failures in the test program.

INDOCTRINATION AND TRAINING

Life Systems personnel will assist in the selection and evaluation of training, indoctrination, and motivation material. Controlled studies will be designed and carried out, as necessary, to determine the effectiveness of these programs in training and motivating employees to design and build more reliable products.

XII. PACKAGING, HANDLING, STORAGE, AND TRANSPORTATION

A packaging, handling, storage, and transportation program has been established to ensure planned reliability attainments through controls applied during all phases of the Apollo program. Protective packaging and handling of all materials, components, and assemblies associated with the Apollo program must conform to strict controls in order to meet the rigid reliability requirements. Protective packaging and handling and engineering surveillances will minimize the inevitable hazards normally encountered in procurement, manufacturing, maintenance, storage, transportation, and other operational processes.

All matters pertaining to preservation, packaging, handling, storage, and transportation are referred to S&ID's Packaging Engineering Department. Included are requirements governing delivery of end-items subcontractor deliveries, supplier's materials and hardware, and in-house manufactured production support and logistic spares support parts, subassemblies, and assemblies. Launch site handling, storage, and retrofit packaging are also monitored. Specific instructions, manuals, training aids, and handbooks are prepared and issued to cover preservation, packaging, handling, storage, and transportation of all end items, spares support, and all field returnable items for manufacturing support.

Based upon a general philosophy that a severe cost penalty or airborne weight penalty shall not be imposed on hardware design by ground handling, storage, and transportation environmental criteria, a packaging and transport program has been established. Protective packaging or special handling equipment and procedures for special handling, transportation, and storage will be developed to prevent exposure of the hardware to environmental conditions in excess of those which its designed capability can withstand without damage or degradation of its performance. Packaging and container design criteria and participation in all preliminary, advanced, and corrective design analyses will be provided to ensure adequate packaging and handling design considerations. Protective packaging and handling provisions are applied on all Apollo project hardware prior to release for purchasing or production. All practical efforts are directed, early in design to preclude or minimize typical "after-the-fact" correction of packaging and handling problems. Utilization of applicable preservation, packaging, handling, storage, and transportation specifications, manuals, and similar control documents are surveyed and directed. Promotion of the most effective applications of the present state-of-the-art are made to maintain the highest reliability objectives. Concurrent investigations of advanced packaging and

handling concepts are being conducted, and assistance will be given in education and training phases covering preservation, packaging, handling, storage, and transportation.

Improved packaging and handling control documents will be developed for application to design and procurement reliability control during manufacture and transportation to and from the launch site. The formal control system has been devised to minimize degradation of hardware during fabrication, test, handling, shipment, and storage. Protective packaging and handling practice callouts will be placed on production drawings and production orders to advance reliability assurance.

An expeditious system has been initiated to report discrepancies in handling and packaging in such a manner that corrective action can be immediately initiated. The S&ID divisional structure has been orientated to operate with the required authority and responsibility to direct and exercise surveillance of all matters pertaining to protective packaging and handling.

XIII. ENGINEERING CHANGES

A system has been established to control and measure the influences of engineering changes on reliability. Basically, this system is in conformance with the standard operating procedure for change control and the configuration control requirements of the Apollo program.

Apollo Engineering is responsible for initiating the change control procedure. It will review all changes to determine their classification and process them in accordance with the Standard Operating Procedure. Reliability review and approval of changes are applicable to the following documents:

Engineering drawings
Engineering orders
Process specifications
Material specifications
Test specifications
Procurement documents

All failure data applicable to the specific item being changed are reviewed, as are in-process problem and discrepancy data applicable to the item being changed. Previous design review recommendations are analyzed. Design analysis checklists are used to ensure adequate screening of the change to determine its influence on reliability. Dispositions of the reliability change review are documented. All changes that require NASA approval will incorporate reliability effects and justification data, as presented on the form shown in Figure 13-1.

RELIABILITY ENGINEERING - MCE
MANPOWER AND COST ESTIMATES FOR
PROPOSED DESIGN CHANGES

EDC/MCR No. _____

Item Name _____

Effectivity _____

1. Description of Change:

2. Description of Work: (See Note 1, below)

1: Brief, concise definitive statements of work to be accomplished by Reliability Engineering based on above description of change. Applicable statements as shown on standard task list may be utilized.

3. Manhours estimated including offsite trips:

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
1963													
1964													
1965													
1966													

Show totals in + or - manhours. Do not show less than 0.1 manhours.

4. Change in costs (Addition or deletion) estimated:
Trips/Destination: _____
Subcontractor/Supplier Reliability: _____
Computers: _____
Other: _____

5. Change in Apollo Reliability Program schedule (delay or accelerate):

6. From the Apollo Reliability Program point-of-view, why should this change be supported?

7. MCR Effectivity is subject to Change Board adjustment. If this change is essential to mission reliability/crew safety, on which end item of the current Master Development Schedule is it mandatory or recommended that this change be incorporated, regardless of effect on schedule? Specify and support.

_____
Analysis Chief, Date

Approved by: _____
B.H. Hershkowitz
Manager
Apollo Reliability Engineering

Figure 13-1. Sample Reliability Engineering MCE

APPENDIX A

OPTIMUM REDUNDANCY AT COMPONENT LEVEL

One of the basic problems arising in design of the Apollo spacecraft is that of developing a reliable system in a short time. Since it cannot be anticipated that reliability improvements of substantial magnitude above the present state-of-the-art can be accomplished within the next few years, S&ID has adopted a philosophy of justified redundancy at the component and subsystem level to obtain an extremely high reliability system, utilizing components of only medium high reliability.

Component redundancy has frequently proved unsuccessful in complex equipment because of necessity of installing additional equipment to detect a failure of one component and actuate switching to the spare or redundant component. Typically, the detect-switch mechanism is too unreliable to accomplish its intended purpose.

Fortunately, the Apollo spacecraft is equipped with a simple, reliable detect-switch device, consisting of the spacecraft crew. Full advantage can be made of the crew by utilizing them as reliability monitors of spacecraft equipment and allowing them to switch to spare components.

The problem then arises as to where component redundancy should be utilized and to what extent. The model described below analyzes the system to determine the degree of redundancy of each component which maximizes system reliability within a fixed weight restraint. Other restraints or combinations of restraints can also be utilized in the same manner.

ANALYTICAL MODEL

A mission simulation model has been developed that relates the mission success and crew safety reliability to the reliability or MTBF of the individual components within the space vehicle, including the effects of redundancy, on-board spares, and backup modes of operation. This model is based on the reliability definitions developed in Section II of this report and considers the operational phases of the Apollo mission. The model has the capability of numerically evaluating the effect of the MTBF of each component on both mission success and crew safety. In optimizing redundancy and on-board spares, each component is evaluated to determine its effect on system reliability. From this, the effect of adding redundancy and spares

can be determined. Knowing the weight of each component, potential candidates for redundancy can be evaluated as to the expected increase of reliability per pound of additional weight.

The procedure for picking spares and redundancy is to rank these candidates with respect to the expected increase of reliability per pound of added weight. Components are then added to the design in their order of effectiveness until sufficient components have been added to meet the reliability requirement within the weight constraint. This determines the design which will achieve the reliability requirement with the minimum weight.

APPENDIX B

SAMPLE CIRCUIT ANALYSIS UTILIZING MANDEX WORST-CASE METHOD

This appendix describes an electronic circuit having built-in reliability deficiencies and presents the methods of developing equivalent circuits for each of its components. The individual equivalent circuits are then combined into an overall equivalent circuit, where a system of N simultaneous linear equations in N unknowns is developed to describe its operation. In the equations, combinations of input parameters are used as coefficients for the unknowns.

The mandex worst-case circuit analysis method is explained, and the method is applied to the system of equations developed for the sample circuit. As the sample circuit is analyzed, indications of inherent deficiencies are pointed out to enable a more thorough understanding of the method.

SAMPLE CIRCUIT

A. INTRODUCTION

In the following sections of this manual, the single-stage common emitter amplifier shown in Figure B-1 will be analyzed using each computer method. In order to illustrate the effectiveness of the methods, certain deficiencies are designed into the circuit:

1. The transistor will cut off under certain conditions.
2. The transistor will saturate under certain conditions.
3. Resistors may dissipate too much power.
4. The gain requirements may not be met.

The first step toward final computer analysis is to draw the equivalent d-c and a-c circuits and formulate their equations. Before accomplishing these tasks, a review of the equivalent circuits for each of the circuit components is in order.

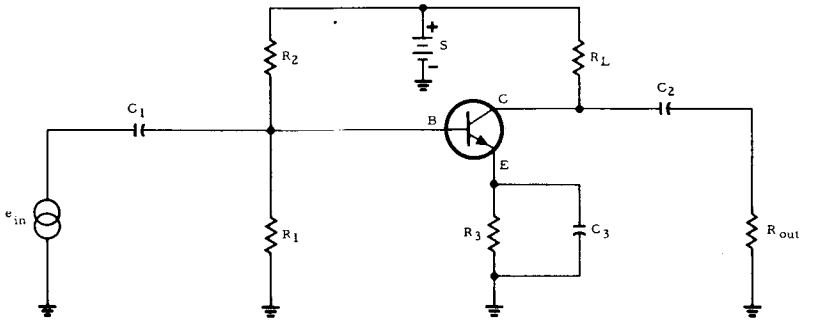


Figure B-1. Single-Stage Common Emitter Amplifier

B. EQUIVALENT CIRCUITS FOR ELECTRONIC COMPONENTS

To facilitate writing of equivalent circuit equations, equivalent circuits for each category of common electronic parts are described below. Only one type of each category is analyzed and may be used as a guide for developing equivalent circuits for similar types. Note that references are not made to circuit applications while deriving the individual equivalent circuits. Instead, each part is isolated and various assumptions are made.

C. CAPACITORS

There is no such thing as the "perfect capacitor." Such factors as leakage currents, nonzero power factors, series resistance, etc, must be considered when deriving its equivalent circuit.

One possible capacitor-equivalent circuit is shown in Figure B-2. The value of C is the nominal value of the capacitor. Parallel resistance R_p represents the d-c leakage resistance, the minimum

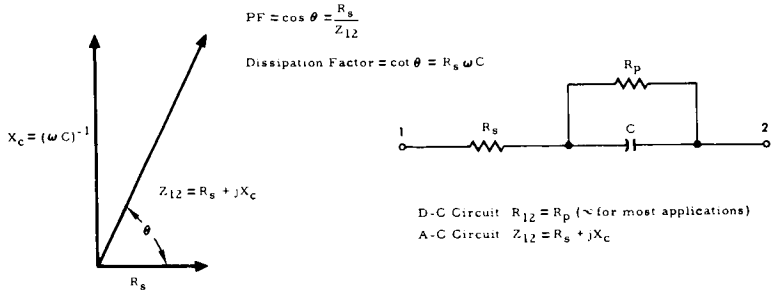


Figure B-2. Capacitor Equivalent Circuit and Phase Relationships

value of which is given in the part specification (e.g., 10,000 megohms). In the majority of applications, R_p can be considered as open circuit. Resistor R_s denotes the equivalent series resistance (esr) of the capacitor. If the equivalent series resistance is not given in the part specification, it can be calculated using the dissipation factor relationship given next to the vector diagram in Figure B-2. The esr of capacitors used by Autonetics is rarely more than a few ohms.

The d-c equivalent circuit for a capacitor is R_p, because C is open to direct current and R_s is minute compared to R_p. In most transistor applications, R_p can be considered infinite, because leakage currents are in the order of a few millimicroamperes. The equivalent a-c circuit can be simplified to $R_s + jX_c$ because of the high resistance of R_p. It is quite unlikely that computer analysis techniques will be applied to circuits where the inductive reactance of the capacitor must be considered.

D. TRANSFORMERS

The equivalent-circuit representation of a transformer depends to a great extent on its design, function in the circuit, and operating frequency. In this section, two equivalent circuits are described: (1) a T-equivalent-circuit and (2) a somewhat simpler circuit to describe a transformer operating at audio frequencies.

The ideal transformer and its associated symbols are shown at the top of Figure B-3. The classical T-equivalent circuit, ignoring capacitances and core losses, is shown at the center of the figure. The modified T-equivalent circuit at the bottom of the figure was derived by defining M' as the ratio of the mutual inductance to the coefficient of coupling ($\sqrt{L_p L_s}$) and letting $M = M' - L_L$. Thus, leakage inductance $L_L = (1 - K) \cdot (L_p L_s)^{1/2}$. Because $M' >> L_L$, $M' - L_L \approx M'$. If the primary (L_{Lp}) and secondary (L_{Ls}) leakage inductances are not equal, they may be individually designated in the primary and secondary windings.

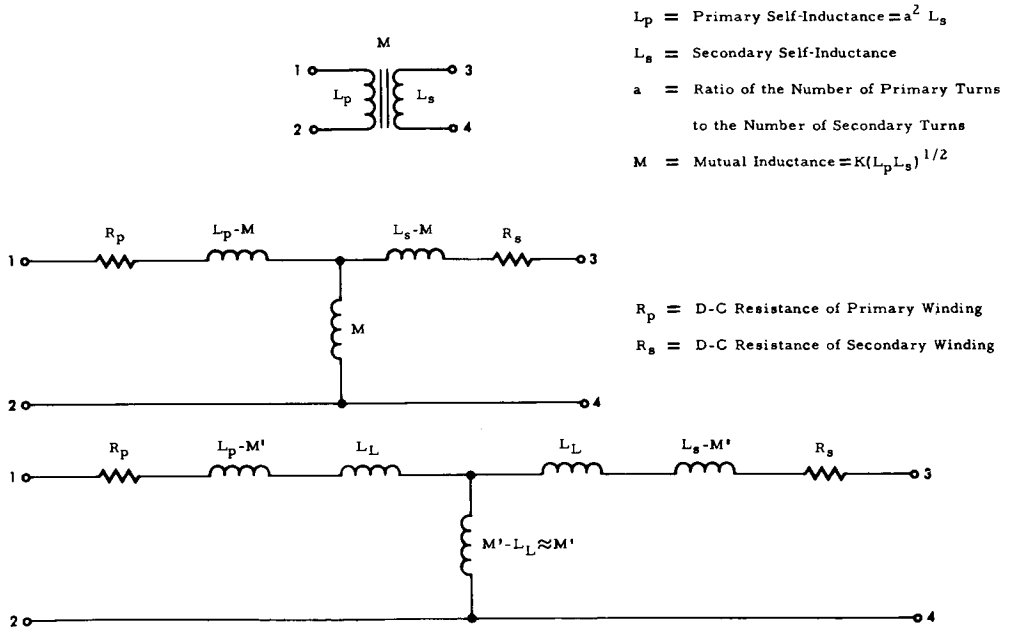


Figure B-3. Transformer T-Equivalent Circuits

The equivalent circuit used for transformers operating at audio frequencies is shown in Figure B-4. The equations for this circuit are as follows:

$$V_p = I_p R_p + j\omega I_p (L_{Lp} + L_p) - j\omega I_s M$$

$$-I_s R_L = I_s R_s + j\omega I_s (L_{Ls} + L_s) - j\omega I_p M$$

This transformer representation for audio frequencies has been used successfully in the analysis of a-f amplifiers. At higher frequencies, the distributed winding capacitance may become significant. In other circuits, a more simplified circuit may be used to eliminate the complex quantities from the equation matrix.

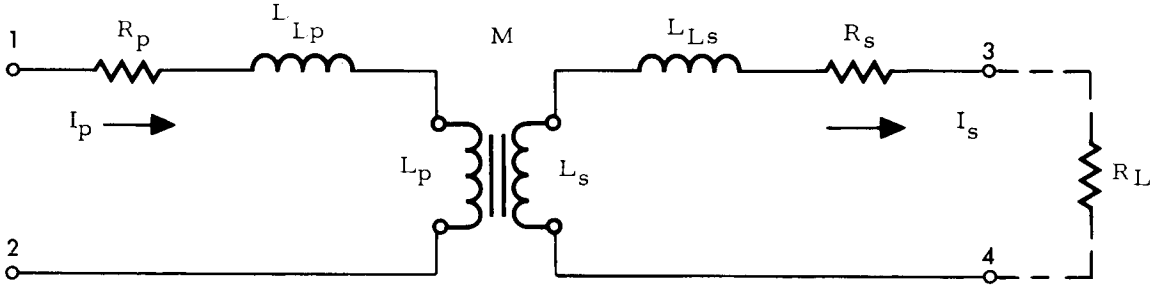


Figure B-4. Transformer Equivalent Circuit at Audio Frequencies

E. DIODES

A diode is relatively easy to represent with linear elements. Effectively, only two possible operating conditions exist: (1) conducting and (2) nonconducting. However, a diode cannot be referred to merely as being forward- or reverse-biased; a certain minimum forward potential is required for conduction to start. When a diode is forward-biased but nonconducting, it must be treated as if it were reverse-biased.

When a diode is nonconducting, it can be represented as a high-value resistor. The d-c characteristics do not abruptly halt as shown in Figure B-5, but continue on as an almost horizontal line into the reverse-biased region. The slope of this line is not readily measurable on the

graph. Therefore, the minimum resistance representing a nonconducting diode must be calculated from the diode specifications. For the SG22 diode (Table B-1), the d-c nonconducting resistance is

$$\frac{2\ v}{0.1 \times 10^{-6}\ amp} = 20\ megohms$$

When the forward bias on a diode exceeds a specified level, forward conduction begins. This specific value can be determined by examining the d-c characteristic curve of the diode. For the SG22 diode, the curve intercepts the voltage axis at 0.55 v (Figure B-5). Linear curve 2 very nearly approximates the characteristic curve below the knee. Therefore, the reciprocal of the slope of curve 2 is the dynamic resistance when diode current is below 1 ma. The slope of curve 2 (0.01 mho) is calculated directly from the graph, and its reciprocal (100 ohms) is placed in series with a zero-impedance voltage source (0.55 v) opposing forward current flow to complete the d-c equivalent circuit shown in Figure B-6.

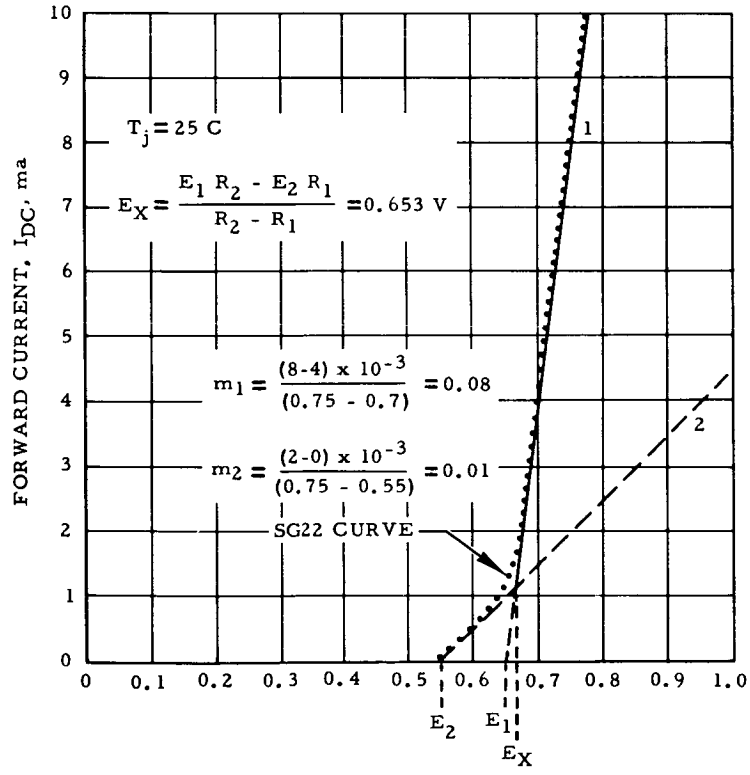
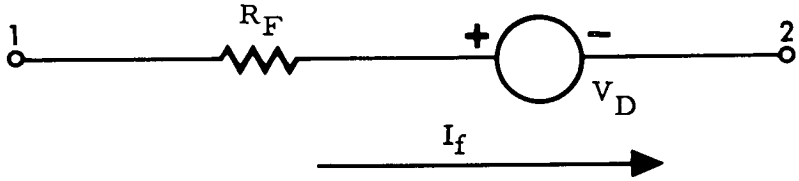

FORWARD CURRENT, I_{DC}, ma
FORWARD VOLTAGE DROP E_{DC}, V
$T_j = 25$ C
$E_X = \frac{E_1 R_2 - E_2 R_1}{R_2 - R_1} = 0.653$ V
$m_1 = \frac{(8-4) \times 10^{-3}}{(0.75 - 0.7)} = 0.08$
$m_2 = \frac{(2-0) \times 10^{-3}}{(0.75 - 0.55)} = 0.01$
SG22 CURVE
1
2
E_2
E_1
E_X

Figure B-5. D-C Characteristics of the SG22 Diode

Table B-1. SG22 Specifications, Ratings, and Characteristics

PARAMETER	VALUE
Specifications at 25 C	
V_f at 1 ma	0.64 V ± 10 Percent
V_f at 100 ma, max	1 V
Maximum Dynamic Resistance	
1 ma, 1 kc	60 ohms
Maximum Inverse Current at 2 V	0.1 μa
Ratings	
Maximum Continuous Current (25 C)	150 ma
Recurrent Peak Current	500 ma
Maximum Surge Current (1 sec)	500 ma
Maximum Ambient Temperature	150 C
Maximum Inverse Voltage	6 V
Typical Characteristics	
V_f at 1 ma	0.64 V ± 10 Percent
V_f at 1 ma	0.90 V ± 10 Percent
Dynamic Resistance	
1 ma, 1 kc	50 ohms
100 ma, 1 kc	0.9 ohm ± 20 Percent
Temperature Coefficient at 1 ma	-2 mv/C



$$V_D = 0.55 \text{ V for } 0.653 > V_{12} \geq 0.55 \text{ V}$$

$$R_F = 100 \text{ ohms for } 0.653 > V_{12} \geq 0.55 \text{ V}$$

$$V_D = 0.64 \text{ V for } V_{12} \geq 0.653 \text{ V}$$

$$R_F = 12.5 \text{ ohms for } V_{12} \geq 0.653 \text{ V}$$

Figure B-6. Conducting D-C Equivalent Circuit for the SG22 Diode

Above 2 ma, the dynamic resistance is the reciprocal of the slope of linear curve 1. This value is 12.5 ohms. Because the extension of curve 1 intercepts the voltage axis at 0.64 v, the voltage source opposing forward current flow is 0.64 v in the equivalent circuit for currents above 2 ma.

Between 1 and 2 ma, the diode resistance is a nonlinear function. Because equivalent circuit parameters must be linear for computer analysis, the conducting portion of the diode characteristic curve is approximated by linear curves 1 and 2, and the computer is programed to use the reciprocal of one or the other slope for the dynamic resistance and its respective voltage intercept for the opposing voltage source. This selection decision is determined by the forward bias voltage at the intersection of the two curves, which is calculated from the following relationship (see Figure B-5):

$$E_x = \frac{E_1 (R_2) - E_2 (R_1)}{R_2 - R_1}$$

where

E_x is the abscissa intersection of curves 1 and 2

E_1 is the curve 1 abscissa intercept

E_2 is the curve 2 abscissa intercept

R_1 is the reciprocal of the curve 1 slope

R_2 is the reciprocal of the curve 2 slope

Thus, by approximating the diode characteristics in the knee region, the diode part parameters have been adapted for computer analysis. This same technique can be used for any nonlinear parameter (i. e., any nonlinear function can be very closely approximated with two or more linear functions, and the computer can be programmed to substitute alternate values above and below their intersections).

F. ZENER DIODES

Zener diodes are seldom used in the forward-conducting region. Therefore, one equivalent circuit for the nonconducting region and one

for the Zener region should be adequate for most applications. In the nonconducting region, a single high-value resistor is used. In the Zener region, the sign of the voltage source in series with the effective diode resistance is reversed from that in a forward-conducting diode.

G. DIODE A-C EQUIVALENT CIRCUITS

Diode a-c equivalent circuits depend on the d-c operating point, with the only element appearing in the circuit being the equivalent dynamic resistance. The value of this resistor is determined by the d-c operating point. When the diode is cut off, the a-c and d-c circuits are identical. In the forward-conducting or Zener regions, the resistance of the d-c circuit is used but the d-c voltage source is not, because all d-c sources must be short-circuited in an a-c equivalent circuit.

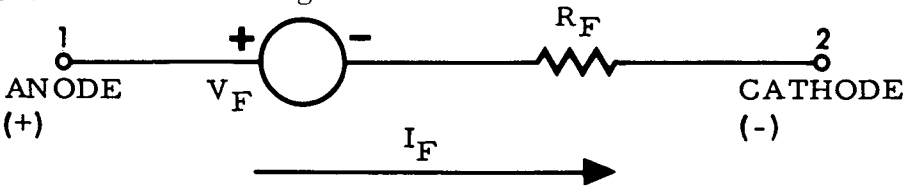
H. CONTROLLED RECTIFIERS

A controlled rectifier is a 3-terminal semiconductor device. Basically, it is a diode with a high forward-voltage drop. The application of a specific signal to its "gate" terminal allows forward conduction at a lower forward-voltage drop. Like the thyratron grid, once forward conduction starts, control by the gate is lost.

The anode-cathode branch and the gate-cathode branch of the controlled rectifier are independent of each other. The anode-cathode branch has three possible states while the gate-cathode branch has two. Thus, there are six possible equivalent circuits for the part. In the following derivation of these equivalent circuits, C35A controlled rectifier specifications and data are used.

When the anode-cathode branch is forward-biased and conducting, it is represented as shown in Figure B-7. To obtain the parameter values of V_F = 0.8 v and R_F = 0.03 ohms, the typical forward characteristics from 1 to 10 amp were redrawn on a linear scale from the semilog manufacturer's curve (Figure B-8, zone A corresponds to zone B) and interpreted as for an ordinary conducting diode. Above 10 amp, the high-current characteristics were approximated with a straight curve whose slope is 100 ohms. Hence, when the instantaneous anode-cathode forward voltage drop equals or exceeds 1.175 v (the intersection of the two curves), V_F is 1.05 v and R_F is 0.01 ohm.

With the gate open, if the anode-cathode branch is forward-biased below the "breakover voltage" for the rectifier, it will not conduct. The breakover voltage for the C35A rectifier is 100 v. The linear approximation of the typical leakage current curve shown in Figure B-9 is used to derive the equivalent forward-biased anode-cathode nonconducting circuit.



For $V_{12} < 1.175$ V: $V_F = 0.8$ V, $R_F = 0.03$ ohm

For $V_{12} \geq 1.175$ V: $V_F = 1.05$ V, $R_F = 0.01$ ohm

Figure B-7. Controlled Rectifier Anode-Cathode Equivalent Circuit During Conduction

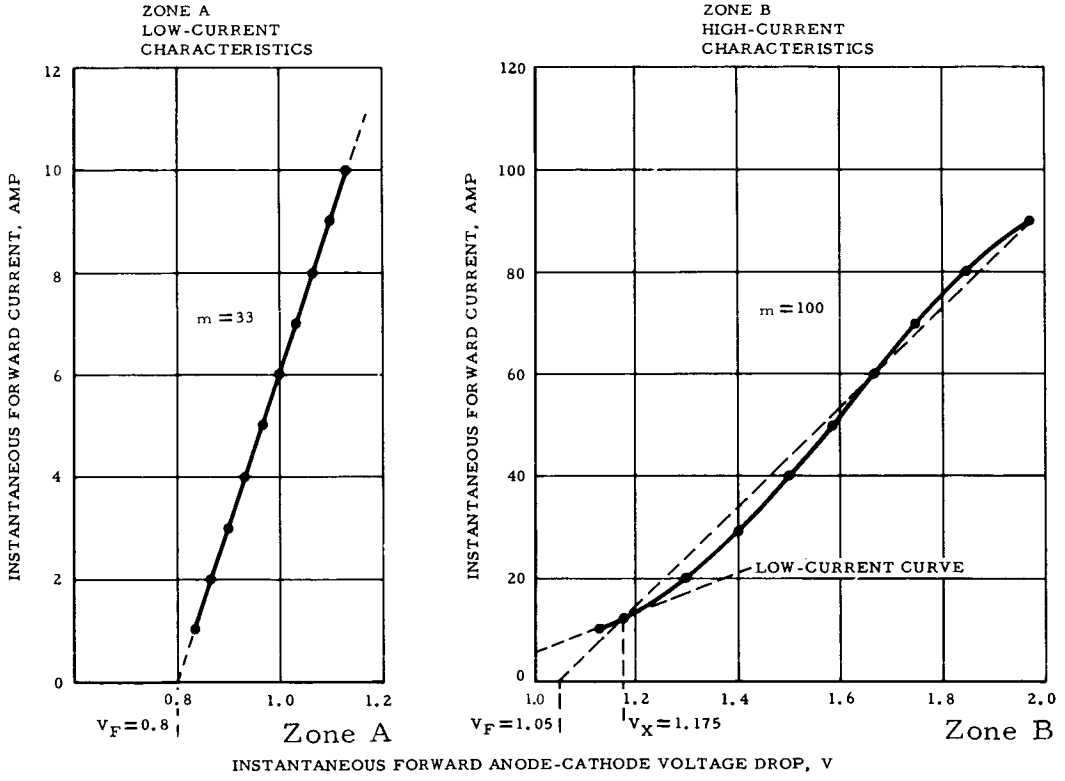


Figure B-8. Linear Plot of the Typical Forward Characteristics of the Anode-Cathode Branch for a Conducting C35A Controlled Rectifier

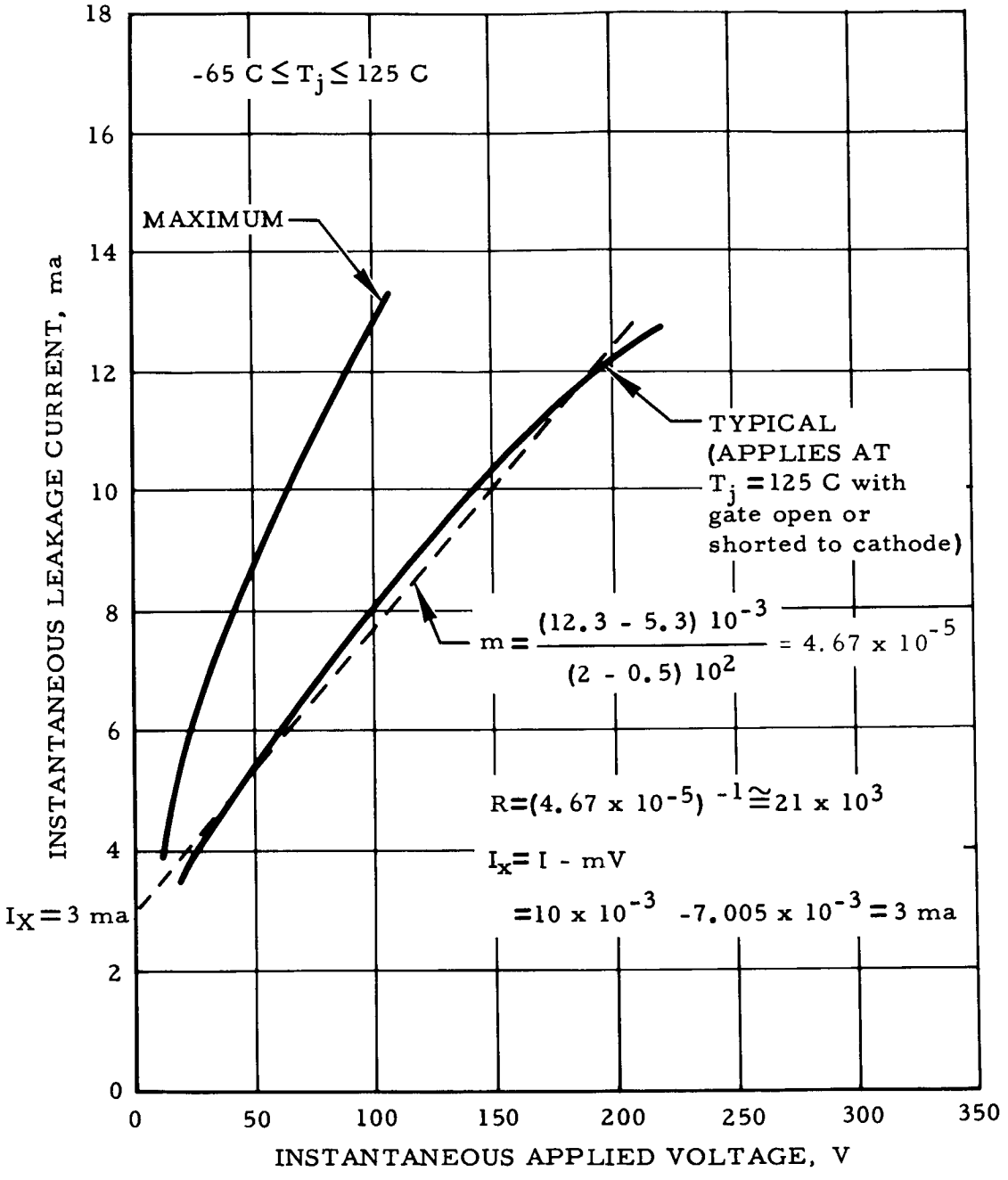


Figure B-9. C35A Controlled Rectifier Anode-Cathode Reverse-Biased and Forward-Blocking Characteristics

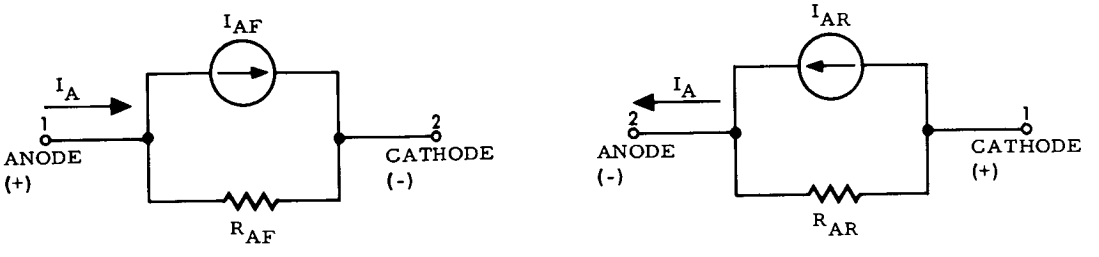
First, the slope of the curve is 4.67×10^{-5} mho, which is equivalent to an effective series resistance of 21,000 ohms. Second, the curve extension intercepts the current axis at 3 ma, which dictates an assisting current generator in the anode-cathode branch to compensate for the shifted abscissa. These two elements are shown as R_{AF} and I_{AF} at the left of Figure B-10. Since a current generator is effectively an infinite impedance, the total circuit resistance to V_{12} is R_{AF} and the total current equals

$$I_A = V_{12} \times R_{AF}^{-1} + I_{AF}$$

When the anode-cathode branch is reverse-biased and non-conducting, its equivalent circuit is identical to the forward-biased circuit except that the current generator and the total current are reversed.

When the gate-cathode branch is conducting, it is represented by a resistor in series with an opposing zero-impedance voltage source as shown in Figure B-11. The values $V_G = 1.0$ v and $R_{FG} = 0.83$ are obtained from curve 1 in Figure B-12. For low voltage-low current magnitudes, the expanded portion of the graph in the upper-right hand corner must be analyzed. Curve 2 in Figure B-12 is the gate cutoff characteristic. Because the linear approximation of this curve passes through the origin only a single resistor of about 125 ohms is needed to represent the cut-off gate-cathode branch of a controlled rectifier.

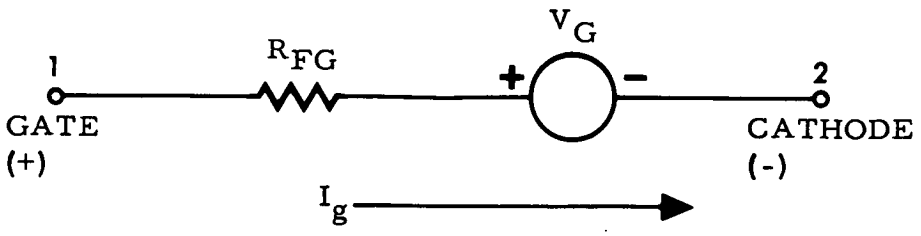
The three anode-cathode and two gate-cathode equivalent circuits derived in the foregoing paragraphs are shown in all their possible combinations in Figure B-13. The ratings and characteristics of the C35A controlled rectifier are given in Table B-2.



$I_A = f(V_{12}) + C$

$R_{AF} = R_{AR} = 21,000$ OHMS

Figure B-10. Cut-off Controlled Rectifier Anode-Cathode Equivalent Circuit



$R_{FG} = 0.83$ OHMS

$V_G = 1.00$ V

Figure B-11. Conducting Gate-Cathode Branch Equivalent Circuit

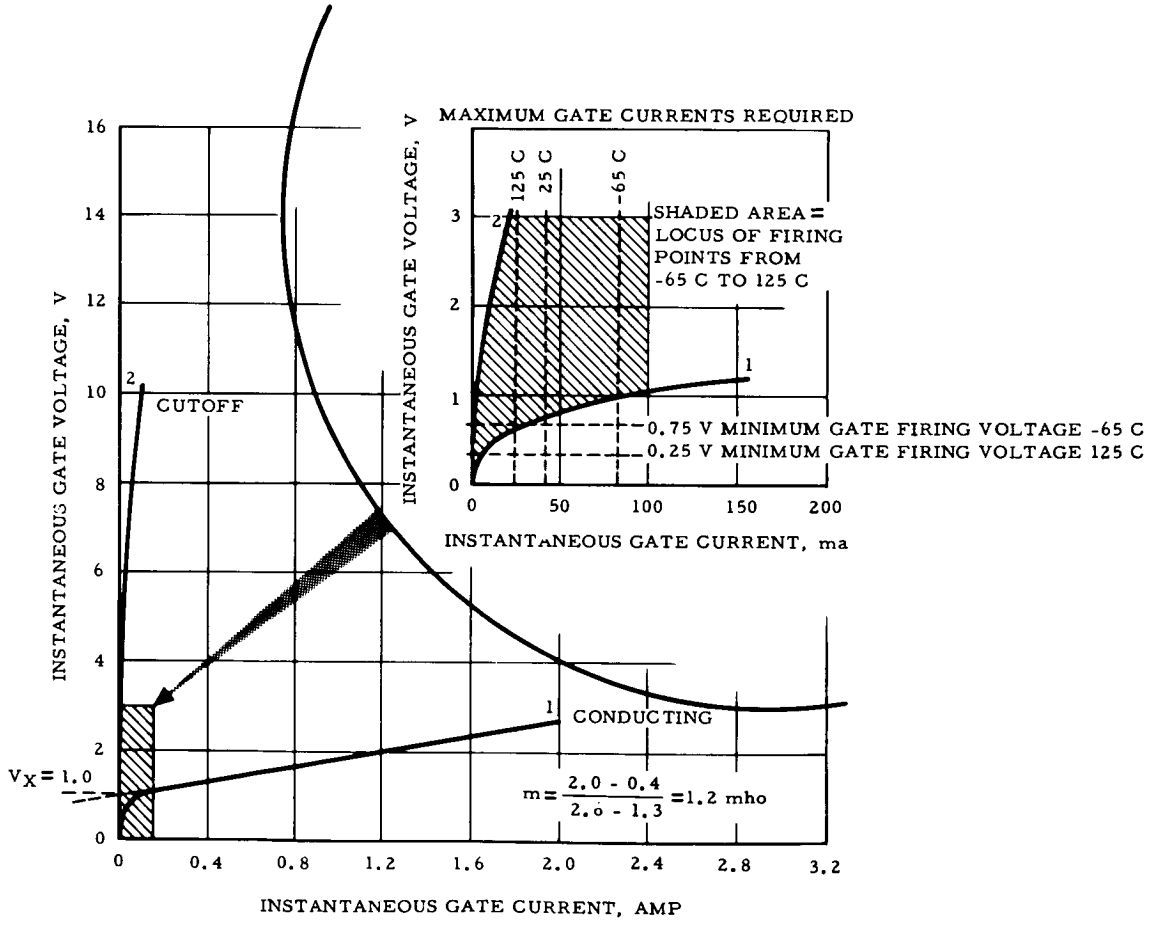

INSTANTANEOUS GATE VOLTAGE, V
INSTANTANEOUS GATE CURRENT, AMP
CUTOFF
CONDUCTING
$V_X = 1.0$
$m = \frac{2.0 - 0.4}{2.0 - 1.3} = 1.2$ mho
MAXIMUM GATE CURRENTS REQUIRED
125 C
25 C
-65 C
SHADED AREA = LOCUS OF FIRING POINTS FROM -65 C TO 125 C
0.75 V MINIMUM GATE FIRING VOLTAGE -65 C
0.25 V MINIMUM GATE FIRING VOLTAGE 125 C
INSTANTANEOUS GATE VOLTAGE, V
INSTANTANEOUS GATE CURRENT, ma

Figure B-12. C35A Controlled Rectifier Firing Characteristics

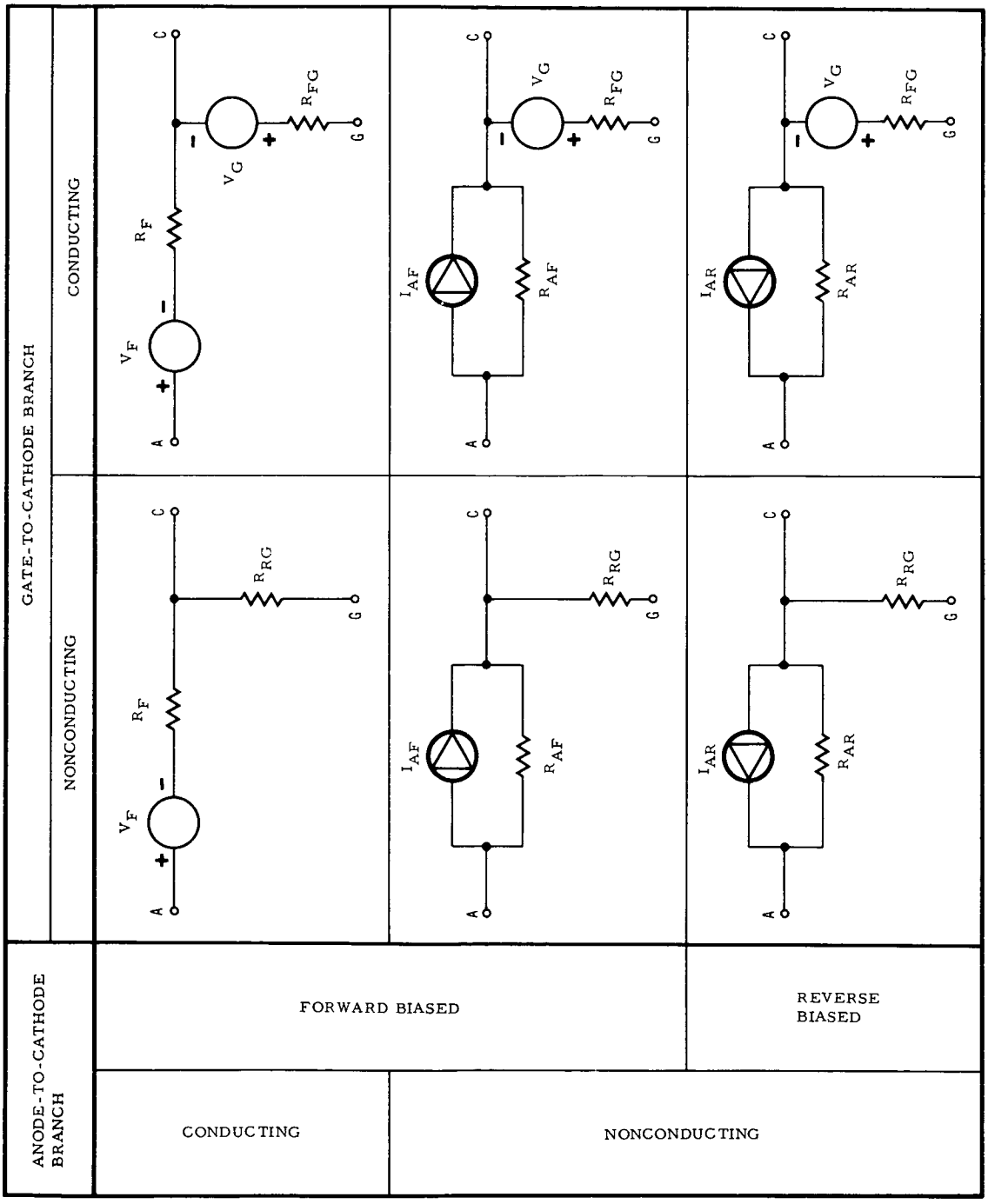


Figure B-13. Controlled Rectifier Equivalent Circuits

Table B-2. C35A Silicon Controlled Rectifier Ratings and Characteristics

MAXIMUM ALLOWABLE RATINGS (RESISTIVE OR INDUCTIVE LOAD)	
Continuous Peak Inverse Voltage (PIV)	100 v
Transient PIV (Nonrecurrent 5 ms)	150 v
V_{RMS} Sinusoidal	70 v
Average Forward Current (I_F)	16 amp
I^2t for Fusing	75 amp^2/Sec ($t \leq 8$
Peak Gate Power	5 w
Peak Gate Current (I_G)	2 amp
Peak Gate Voltage (V_G)	
Forward	10 v
Inverse	5 v
Storage Temperature	-65 C to 150 C
Operating Temperature	-65 C to 125 C
Stud Torque	30 in.-lb
CHARACTERISTICS	
Minimum Forward Breakover Voltage (V_{BO})	100 v
Maximum Reverse (I_R) or Forward (I_S) Leakage Current (Full-Cycle Average)	6.5 ma
Maximum Forward Voltage (V_F) (Average)	0.86 v
Maximum Gate Current to Fire	25 ma
Gate Voltage to Fire (V_{GF})	
Maximum	3 v
Minimum	0.25 v
Maximum Thermal Resistance (R_T)	2 C/w (jct to stud)
Typical Holding Current (I_H)	10 ma
Typical Gate Current to Fire (I_{GF})	10 ma @ + 1.5 v Gate-Cathode
Typical Reverse (I_R) or Forward (I_S) Leakage	See graphs
Typical Delay Time (t_d)	0.5 - 1.5 μsec
Typical Rise Time (t_r)	0.5 - 3.0 μ sec
Typical Turn-on Time ($t_d + t_r$)	1.0 - 4.5 μ sec
Typical Turn-off Time (t_o)	10 - 20 μsec

I. TRANSISTORS

Transistors require different equivalent circuits for each of their operational modes: (1) cutoff, (2) cutoff-to-active transistion, (3) active, (4) active-to-saturation transition, and (5) saturation. Example circuits for each mode are derived in the following paragraphs using the 2N657 npn diffused-junction silicon transistor in the grounded emitter configuration. Specifications for the grounded emitter characteristics of the 2N657 transistor are shown in Table B-3 and Figure B-14.

An ordinary transistor is a 3-terminal device having an input terminal, an output terminal, and a common-ground terminal. Analyzing the device from a blackbox viewpoint, it consists of an input-to-ground impedance (Z_{in}) and an output-to-ground impedance (Z_{out}). In the case of a grounded emitter transistor, Z_{in} is designated Z_{BE} and Z_{out} is designated Z_{CE}. Z_{BE} is determined by analyzing the base characteristics of the transistor and Z_{CE} is determined by analyzing the collector characteristics.

The typical collector characteristics for a grounded emitter 2N657 transistor are shown in Figure B-14A. The saturation region is to the left of the $m = 1/R_{cx}$ curve, the active region is between the $m = 1/R_{cx}$ and the $I_B = 0$ curves, and the cutoff region is below the $I_B = 0$ curve. The typical base characteristics are shown in Figure B-14B. Note, that the I_B vs V_{BE} curve is similar to the diode characteristic curve of Figure B-5.

When a transistor is operating in the saturation region, the collector characteristic curve is linear with a slope equal to the reciprocal of the saturation resistance (designated R_{cx} or R_{cs}). According to Table B-3, maximum R_{cx} for the 2N657 is 25 ohms. This is depicted as the MAX R_{cx} curve in Figure B-14A. The value of the typical R_{cx} shown on the collector characteristic graph is (2-0) v/(160-0) x 10^{-3} amp = 12.5 ohms. Since this curve passes through 0, 0, no current or voltage generator is required and Z_{CE} can be represented as R_{cx} = 12.5 ohms, as shown in Figure B-15A.

Table B-3. Design Specifications for the 2N657 Transistor at T_j = 25 C

PARAMETER	TEST CONDITIONS	VALUE	UNIT
MAXIMUM AND MINIMUM DESIGN VALUES			
Breakdown Voltage, BV_{CBO}	I_C = 100 ma, I_E = 0	100 min	V
Breakdown Voltage, BV_{CRO}	I_C = 250 ma, I_B = 0	100 min	V
Breakdown Voltage, BV_{EBO}	I_E = 250 ma, I_C = 0	8 min	V
Collector Cut-off Current, I_{CBO}	V_{CB} = 30 V, I_E = 0	10 max	ma
Current Transfer Ratio, h_{FE}	V_{CE} = 10 V, I_C = 200 ma	90 max	-
		30 min	
Input Impedance, h_{ie}	V_{CE} = 10 V, I_B = 8 ma	500 max	ohm
Saturation Resistance, R_{CX}	I_C = 200 ma, I_B = 40 ma	25 max	ohm
TYPICAL DESIGN VALUES			
Input Impedance, h_{ie}	V_C = 30 V, I_C = 30 ma	350	ohm
Forward Current Gain, h_{fe}	V_C = 30 V, I_C = 30 ma	60	-
Reverse Voltage Gain, h_{re}	V_C = 30 V, I_C = 30 ma	400	-
Forward Current Gain at 2 mc, h_{fe}	V_C = 30 V, I_C = 30 ma	6	-
Output Admittance, h_{oe}	V_C = 30 V, I_C = 30 ma	90	μmho
Emitter Cut-off Current, I_{EBO}	V_{EB} = 5 V, I_C = 0	0.1	ma
Collector Cut-off Current at 150 C, I_{CBO}	V_{CB} = 30 V, I_E = 0	60	ma

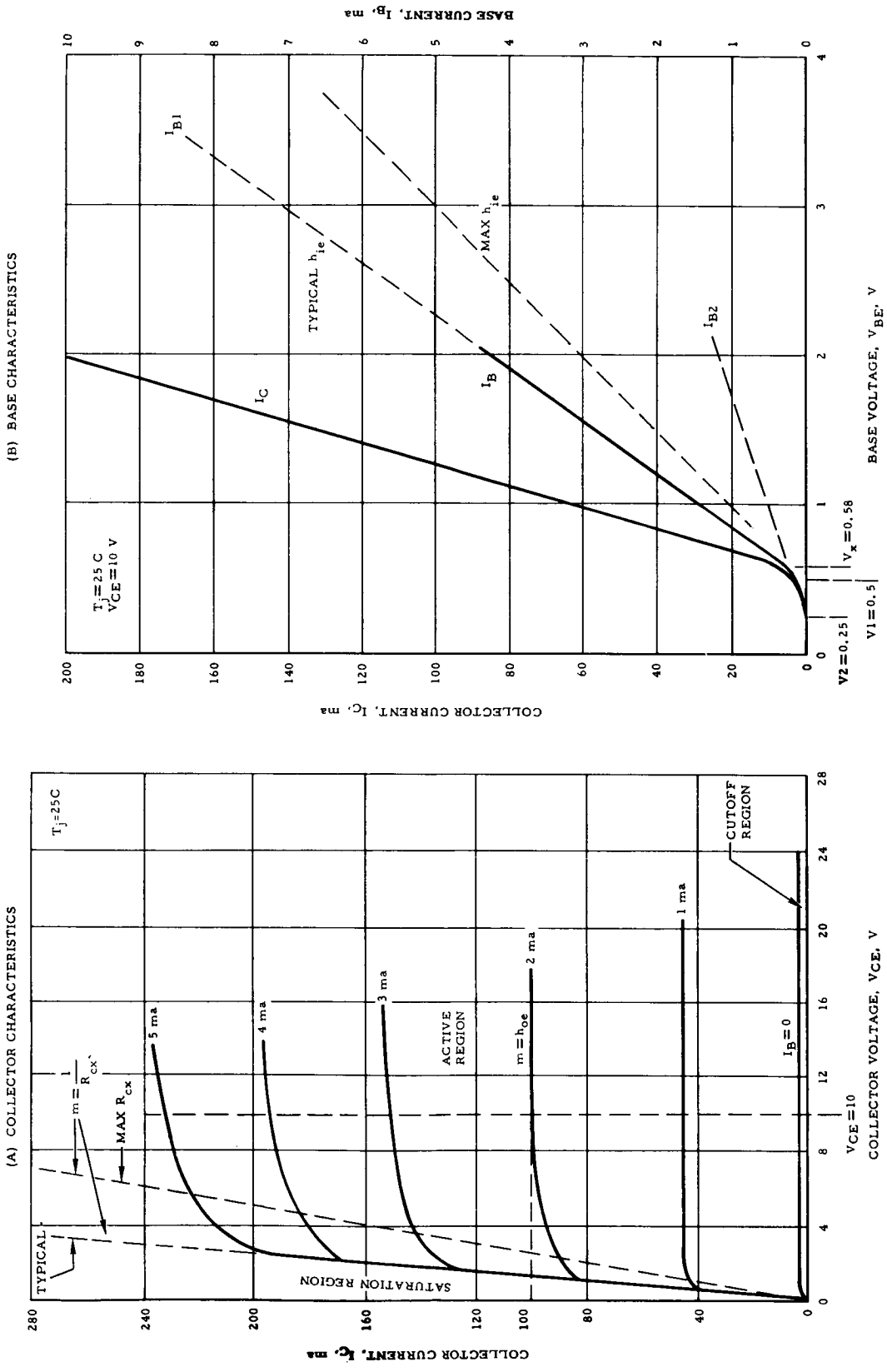


Figure B-14. Characteristics of the 2N657 in the Common Emitter Configuration

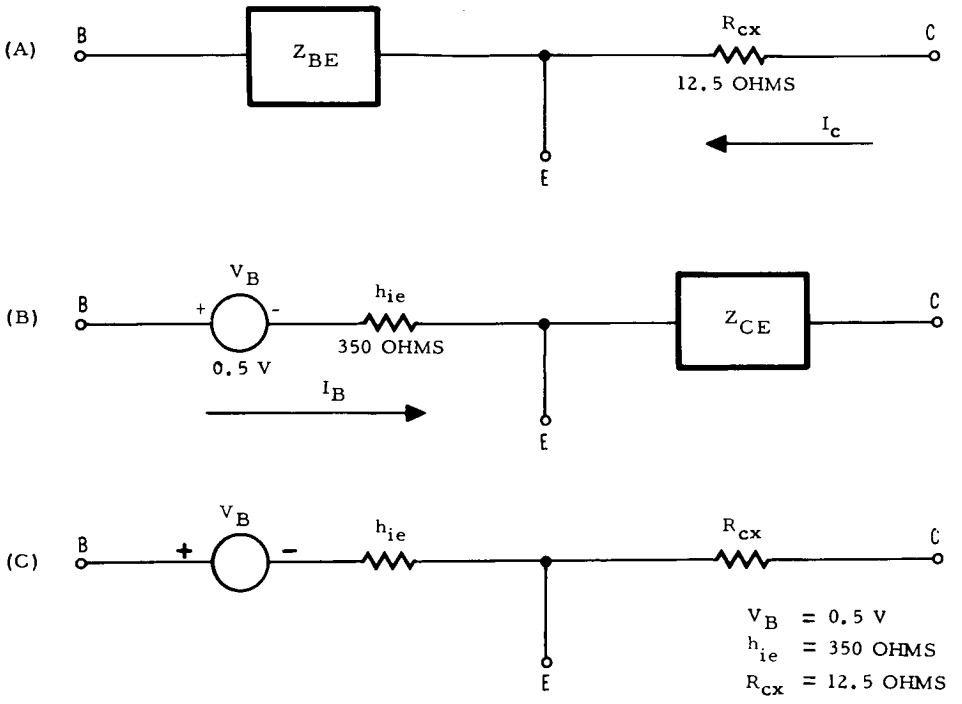


Figure B-15. Equivalent D-C Circuit for a Saturated Grounded Emitter NPN Transistor

As previously mentioned, the base characteristics of a grounded emitter transistor are similar to those of a diode; the resistance curve intercepts the voltage axis leading to an equivalent circuit of a zero-impedance voltage source in series with a resistance whose value is the reciprocal of the I_B versus V_{BE} curve slope as shown in Figure B-15B. When the transistor is operating in the saturation region, the base normally is operating on the I_{B1} portion of the curve. Therefore, the typical value of h_{ie}, the input impedance, can be either 350 ohms as specified in Figure B-14A or (2-1) v/(4.2-1.4) ma = 357 ohms as calculated from Figure B-14B. Voltage source V_B in Figure B-15B is 0.5 v opposing the base current, because I_{B1} intercepts the abscissa at that value. Combining the collector and the base equivalent circuits derived above results in the composite d-c equivalent circuit shown in Figure B-15C for a grounded emitter npn transistor operating in the saturation region.

In the active region, the base-to-emitter circuit is essentially the same as for the saturation region. However, for low values of base

current, operation is below the knee of the I_B versus V_{BE} curve. Thus, for base-to-emitter bias voltages below a certain value, different values of h_{ie} and V_B must be used. These values are 1500 ohms and 0.25 v, respectively, and the transition point is 0.58 v as shown in Figure B-16. V_x is calculated from the relationship

$$V_x = \frac{h_{ie2} V_1 - h_{ie1} V_2}{h_{ie2} - h_{ie1}}$$

where

V_x = abscissa coincidence of curves I_{B1} and I_{B2}

V_2 = the abscissa intercept of curve I_{B2}

h_{ie1} = the reciprocal of the I_{B1} slope

h_{ie2} = the reciprocal of the I_{B2} slope

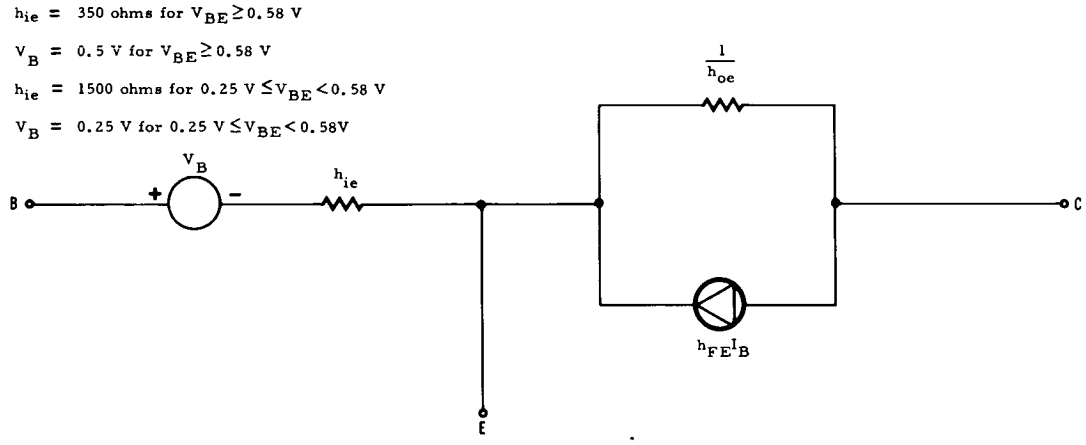

h_{ie} = 350 ohms for $V_{BE} \geq 0.58$ V
V_B = 0.5 V for $V_{BE} \geq 0.58$ V
h_{ie} = 1500 ohms for $0.25 \text{ V} \leq V_{BE} < 0.58$ V
V_B = 0.25 V for $0.25 \text{ V} \leq V_{BE} < 0.58$V
V_B
h_{ie}
$\frac{1}{h_{oe}}$
B
C
E
$h_{FE}I_B$

Figure B-16. D-C Equivalent Circuit for a Grounded Emitter NPN Transistor Operating in the Active Region

The output impedance of a transistor in the active region is the reciprocal of the slope of the constant-base-current curves on the collector characteristic graph. Because these slopes vary slightly from the bottom to the top of the graph, it is most convenient to use the reciprocal of the typical output admittance (h_{oe}) given in the tabulated design specifications. For the 2N657 transistor, the typical output admittance is 90 μ mhos. Hence, the value of output impedance $1/h_{oe}$ in Figure B-16 is 1.1×10^4 = 11,000 ohms.

Each of the constant-base current curves, when approximated by a straight line with a slope of h_{oe} extended to the left, intercepts the I_c axis, indicating that an infinite impedance current generator is required in the collector equivalent circuit. The amount of current produced by this generator depends on base current I_B and transistor current transfer ratio h_{FE} (also referred to as beta). On the collector characteristics graph, h_{FE} at I_C = 100 ma is 50. Using this value for h_{FE} rather than the maximum or minimum specification values of 30 or 90, the generator in the collector branch of Figure B-16 produces a current of $50I_B$, thus satisfying the gain relationship of the transistor. For extremely low-base currents it may be necessary to use the cutoff equivalent circuit to include the effects of the collector cutoff current.

When a transistor in the grounded emitter configuration is cut off, it is operating below the I_B = zero curve. For this condition a certain collector cutoff current, I_{CBO}, flows. This current is a function of the collector-to-base bias. As specified in Table B-3, the maximum I_{CBO} for the 2N657 transistor with V_{CB} = 30 v is 10 μa. Thus, the minimum collector cutoff impedance is 3 megohms. Experiments have shown that a typical value of I_{CBO} at V_B = 30 v is 0.6 μa. Hence, the typical collector-to-base equivalent circuit for a cut-off 2N657 transistor is a 50-megohm resistor (R_{CB}) paralleling an infinite-impedance 0.6-μa generator (I_{CBO}) as shown in Figure B-17.

Similarly, an emitter cutoff current (I_{EBO}) that is a function of the emitter-to-base voltage (V_{EB}) flows in a cut-off transistor. For the 2N657, a typical I_{EBO} of 1 μa flows when V_{EB} = 5 v as specified in Table B-3. Thus, the emitter-to-base branch of the cut-off transistor consists of a 50 megohm resistor (R_{EB}) in parallel with an infinite-impedance 1-μa current generator opposing normal emitter-current flow.

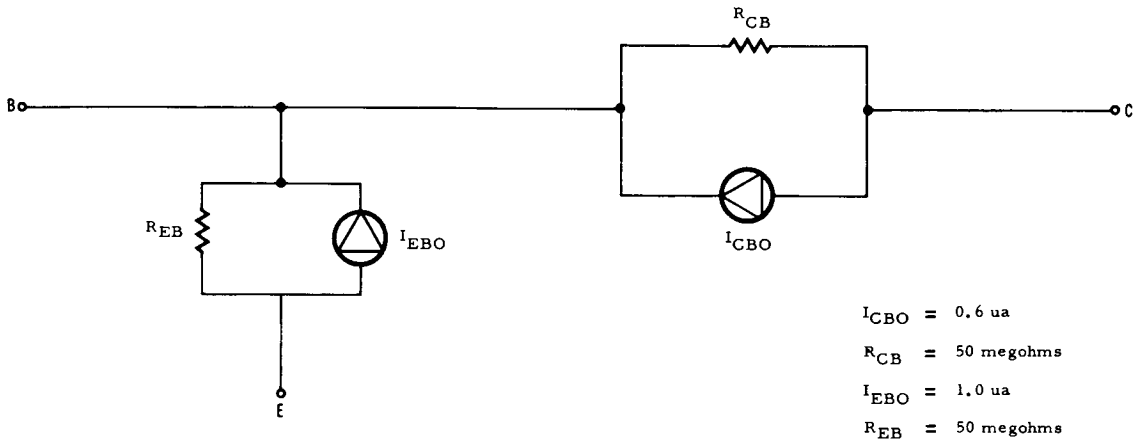


Figure B-17. D-C Equivalent Circuit for a Cut-Off 2N657 Transistor

Current flow out of the base will be resolved when $I_{EBO} + I_{CBO}$ is subtracted from V_{BE}/R_{EB} in the grounded emitter configuration analysis. When variation limits are specified, take special care to assure that the generators do not provide more than the short-circuit current of the circuit through the transistor. Otherwise, a node voltage in the analysis may become greater than its respective supply voltage.

Transistor behavior, when leaving one region and entering another, is of particular interest in the analysis of a circuit. For example, a changing circuit parameter may increase the base voltage of a cut-off grounded emitter npn transistor to a point where the transistor enters the active region. In this case, the cut-off equivalent circuit is not valid after V_{BE} exceeds the cut-off limit. Other instances may occur where the mode of operation is disturbed by other circuit elements, particularly if the transistor is not strongly biased into a particular region.

The circuit that has been successfully used to represent a grounded emitter npn transistor between the cut-off and active regions is shown in Figure B-18. Essentially, it is a combination of the active and cut-off equivalent circuits of Figures B-16 and B-17.

The base characteristic curve (Figure B-14B) shows that the base current is very nearly zero up to $V_{BE} = 0.25$ v. Therefore, I_B should be made zero for all values of V_{BE} below 0.25 v by setting V_{BE} equal to V_B. This has the effect of giving the base an extremely high input impedance. The value of h_{oe} should be 1×10^{-8} mho to present a high impedance from the collector to the emitter. Since $I_B = 0$, the output of current generator $h_{FE}I_B$ also will be zero. The value of h_{ie} is unimportant in this case, while R_{CB} and I_{CBO} are as specified for a cut-off transistor.

As V_{BE} increases above 0.25 v, base current starts to flow, and the transistor enters the active region represented by curve I_{B2} in Figure B-14B. For this region $V_B = 0.25$ v, $h_{ie} = 1500$ ohms, and R_{CB} and I_{CBO} are as previously specified. Output admittance h_{oe} and current transfer ratio h_{FE} depend on I_B. When $I_B = 0.1$ ma, h_{FE} is very nearly zero and $h_{oe} = 15 \times 10^{-6}$ mho. When $0.1 \text{ ma} < I_B < 0.2$ ma, $h_{FE} = 10$ and $h_{oe} = 30 \times 10^{-7}$ mho. When $I_B > 0.2$ ma, the transistor may enter the region defined by the I_{B1} curve. Crossover point V_x is computed as shown in the paragraph covering the base-to-emitter circuit.

With the value of V_x known, V_{BE} may be compared with it and, if $V_{BE} > V_x$, the equivalent-circuit values should correspond to those of the transistor operating on curve I_{B1}. Conversely, if $V_x > V_{BE}$, the values corresponding to curve I_{B2} should be used. V_X should be redetermined each time the computer varies a parameter; if the transistor normally is operating on curve I_{B2} and h_{ie2} is being varied, the intersection point may be moved past the operating point. This is highly unlikely, but precautions should be taken to preclude the possibility.

Operation of a transistor going from the saturation to active region is treated essentially the same, except that the equivalent circuit is similar to that for an active transistor (Figure B-16). When the transistor

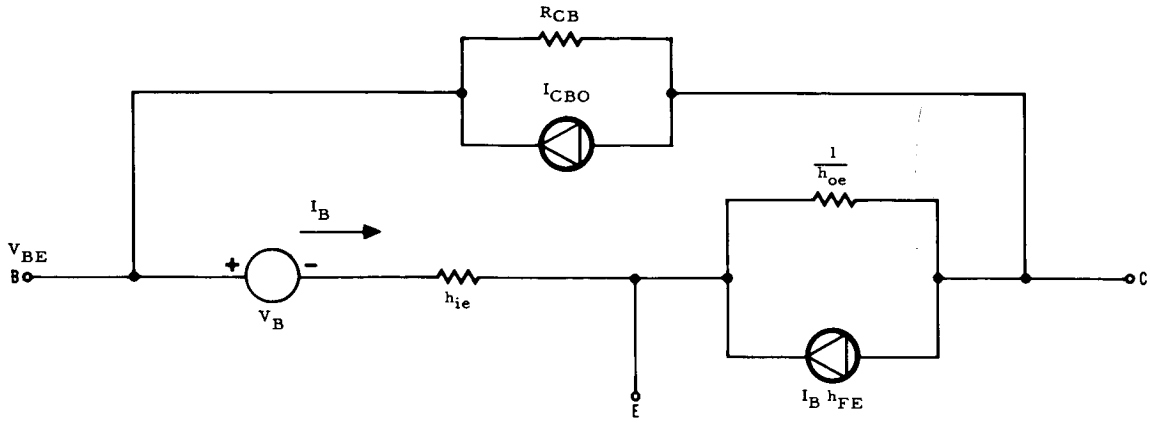


Figure B-18. D-C Equivalent Circuit for a Grounded Emitter NPN Transistor Operating Between the Cut-off and Active Regions

is saturated, the collector-to-emitter resistance is R_{cx} and $I_B h_{FE}$ is zero, and the other parameters are as specified for saturated transistors. For the active region, the parameters are as specified in Figure B-16. The point at which the transistor leaves the saturation region and enters the active region is determined by drawing a load line on its characteristics to determine the minimum values of I_B and I_C required for saturated operation.

It is very unlikely that a transistor will be saturated with a low collector current. Consequently, when leaving the saturated region, operation will be on curve I_{B1} and its parameter values will normally be for $V_{BE} > V_x$. If, by some chance, operation were to switch to the I_{B2} curve, parameter values would have to be adjusted accordingly. Which curve to use depends entirely on the amount of base current.

Values for the transistor parameters in the preceding paragraphs were obtained primarily from the transistor specifications and typical characteristics. For quantities not evident in these sources, persons thoroughly familiar with the 2N657 transistor were consulted.

Minor difficulties may be experienced in obtaining values for h_{ie} and h_{oe}, because most transistor specifications and data are given in terms of the grounded-base configuration. Expression of grounded emitter parameters in grounded-base terms is illustrated in Figure B-19. A and B show normal grounded emitter and base configurations. C shows a grounded-base transistor rotated to the grounded emitter configuration. Finally, D shows the grounded emitter parameters in grounded-base terms.

All of the transistor equivalent circuits derived above are for d-c operation. Basically, these same circuits may be used for a-c operation if the "h" parameters are considered to be constant and purely resistive. These parameters can be constant only if the d-c bias currents vary over a limited range.

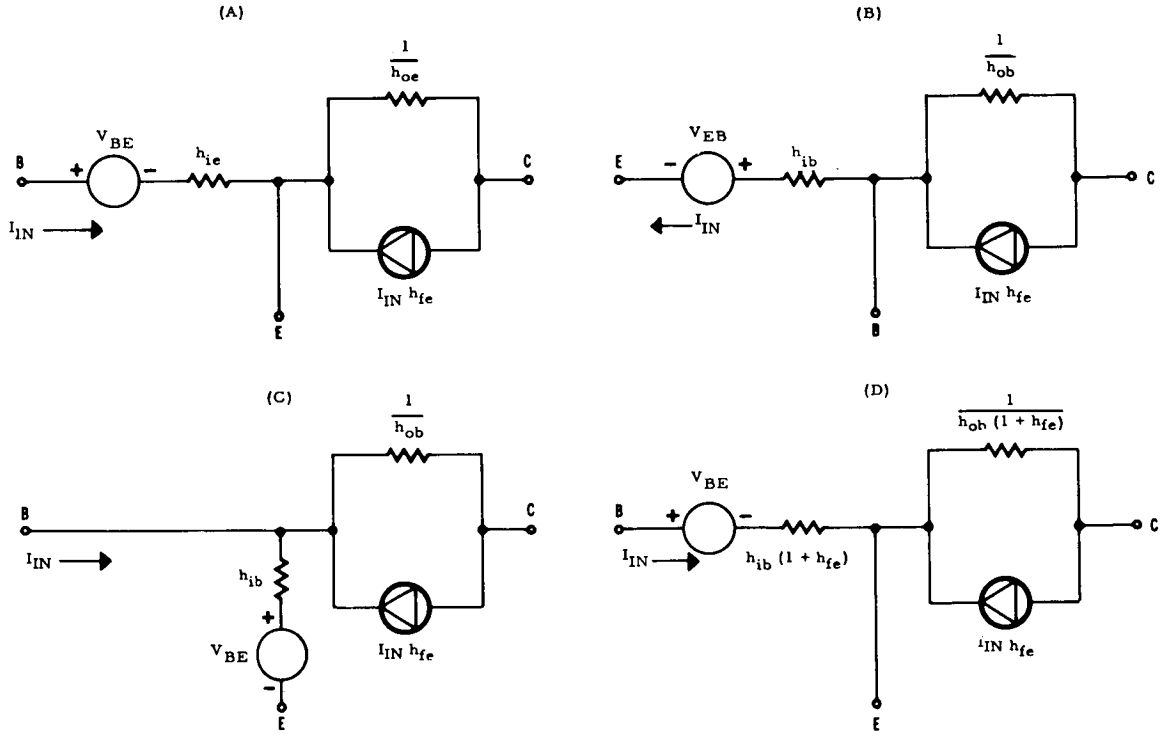


Figure B-19. Expressing Grounded Emitter Input Impedance and Output Admittance in Grounded-Base Terms

For a-c operation, only the active mode should be considered. Hence, the input signal cannot be so large that it will saturate or cut off the transistor. To determine input signal limits, the quiescent operating point must be known. This is determined by a d-c analysis in the active region. Because only dynamic conditions are considered in an a-c analysis voltage source, V_B is not used. The value of h_{ie} remains the same because h_{ie} is defined as the slope of the base characteristic and not as the d-c base voltage divided by the d-c base current. Likewise, $1/h_{oe}$ is the same as for the active d-c equivalency. The current generator in the collector branch is basically the same as for the d-c analysis, with a slight difference in symbolism; where the d-c gain is designated h_{FE}, the a-c gain is designated h_{fe}. Similarly, the d-c base current is designated I_B, and the a-c base current is designated i_b. Because it normally may be neglected, voltage feedback generator $h_{re} V_c$ is not included in the base circuit. If the transistor type or circuit dictates its use, this generator may be included.

Transistor capacitances (e. g. , collector capacitance C_{ob}) were not mentioned in the d-c and a-c equivalent circuits because: (1) capacitances appear as almost infinite impedances in d-c circuits and, (2) their effects are minute in a-c circuits except at the higher frequencies. In the event a particular transistor has a capacitance whose effect would be noticeable at the operating frequency of the circuit, the capacitance must be included in the equivalent circuit. The equivalent circuit to be used is so dependent on the circuit configuration, that a general method of representation is not included in this report.

J. UNIJUNCTION TRANSISTOR

Inasmuch as the unijunction transistor is a relative newcomer to the semiconductor field, some background information is provided below to facilitate the understanding of the derived equivalent circuits.

The unijunction transistor consists of a bar of n-type silicon with a resistive contact at each end (base 1 and base 2) on one side and a rectifying-type contact (the emitter) on the opposite side near base 2 (see Figure B-20). In the most commonly used circuits, base 1 (B_1) is close to ground potential and a positive bias voltage (V_{BBO}) is applied to base 2 (B_2). With no emitter current flowing, the silicon bar acts

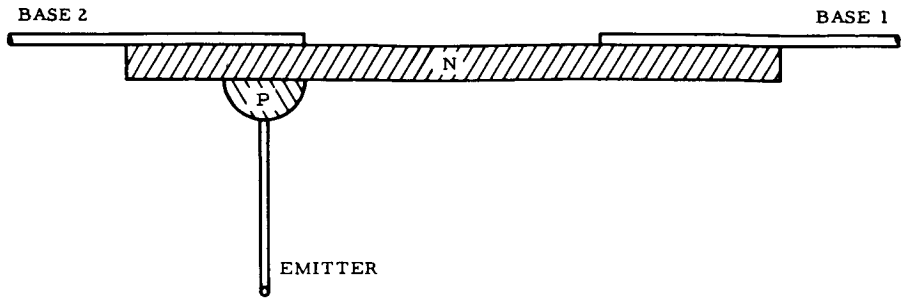


Figure B-20. The Unijunction Transistor

as a voltage divider with a certain fraction of V_{BBO} appearing at the emitter (E). This fraction of V_{BBO} is known as the intrinsic standoff ratio and is designated η. If the emitter voltage (V_E) is less than ηV_{BBO}, the emitter junction is reverse biased and a reverse leakage current (I_{EO}) flows between B_2 and E. In this cut-off condition there is a relatively high interbase resistance (R_{BBO}) limiting interbase current (I_{BBO}) (see Figure B-21).

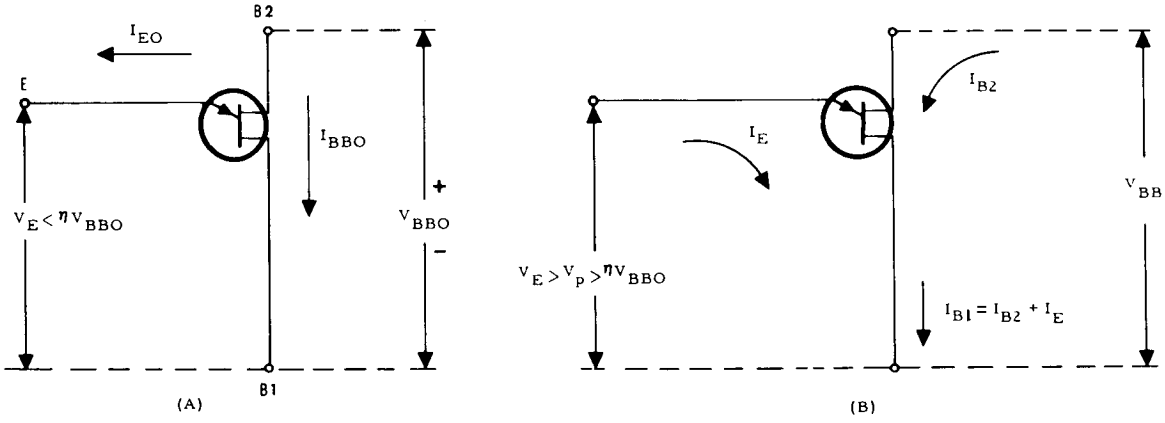


Figure B-21. Cut-Off (A) and Conducting (B) Unijunction Transistor

When V_E reaches a value V_P (which is slightly greater than ηV_{BBO}), emitter current (I_E) flows between E and B_1. This current consists primarily of holes injected into the silicon bar by the emitter. These holes move to B_1 and increase the number of free electrons there to decrease the resistance near B_1. This decreased resistance results in an increase of interbase current. As shown in Figure B-21B, $I_{B1} = I_{B2} + I_E$. Thus, the increase in I_{B2} appears as a current gain in I_{B1} relative to I_E.

Peak emitter voltage V_P is the voltage required to "fire" the transistor, and is defined as

$$V_P = \eta V_{BBO} + V_D$$

where V_D is the temperature correction factor. V_D is defined as

$$V_D = \frac{200}{T_j}$$

where T_j is the junction temperature in Kelvin degrees. Parameter V_D is approximately equal to $V_V - V_O$ in Figure B-22. V_O is obtained by extending the emitter saturation curve to intercept the V_E axis as a diode characteristic. Thus, V_O equals the forward threshold voltage of the fictitious diode.

Note that the emitter curve indicates a negative resistance characteristic in the active region. Hence, the limiting factor for maximum emitter current is the configuration of the emitter circuit. If the available emitter current (I_E) is greater than the minimum current required to fire the transistor at V_P (I_P), the transistor will leave the cut-off region. If the available I_E is greater than I_V, the point at which the transistor goes into the saturated region, the transistor will enter the saturated region and assume a positive resistance characteristic.

The relaxation oscillator circuit of Figure B-23 is a typical application for a unijunction transistor and is used to develop an equivalent circuit for operation in the saturated region. As capacitor C is charged

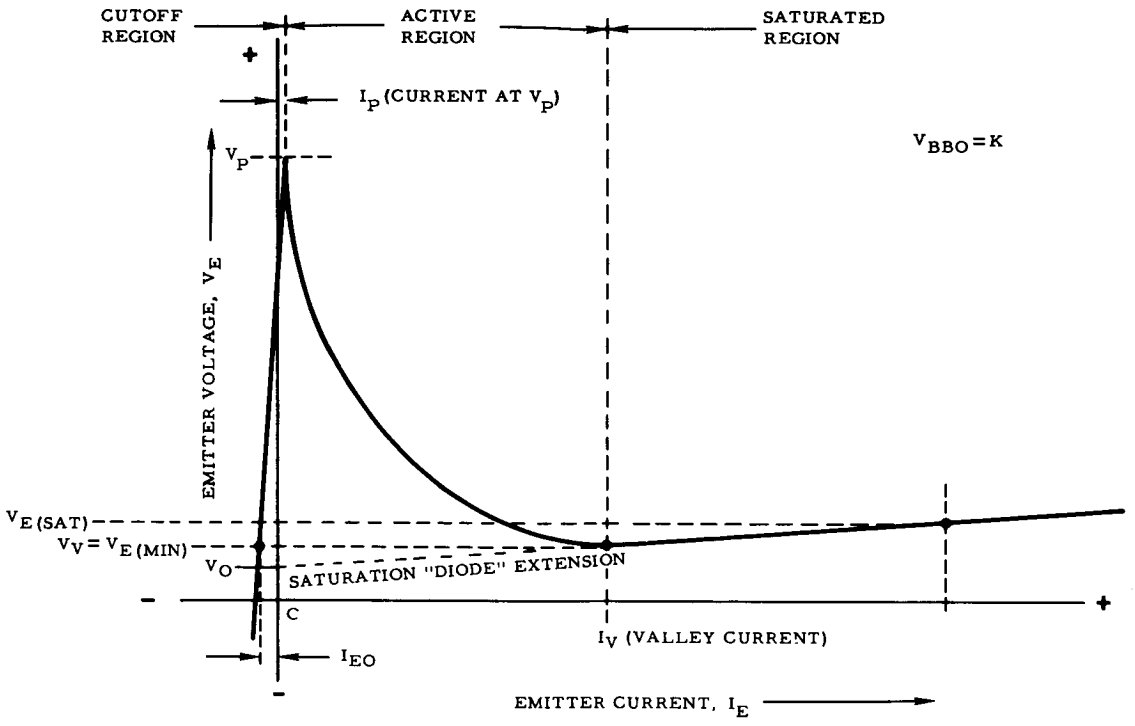


Figure B-22. Typical Static Emitter Characteristics of a Unijunction Transistor

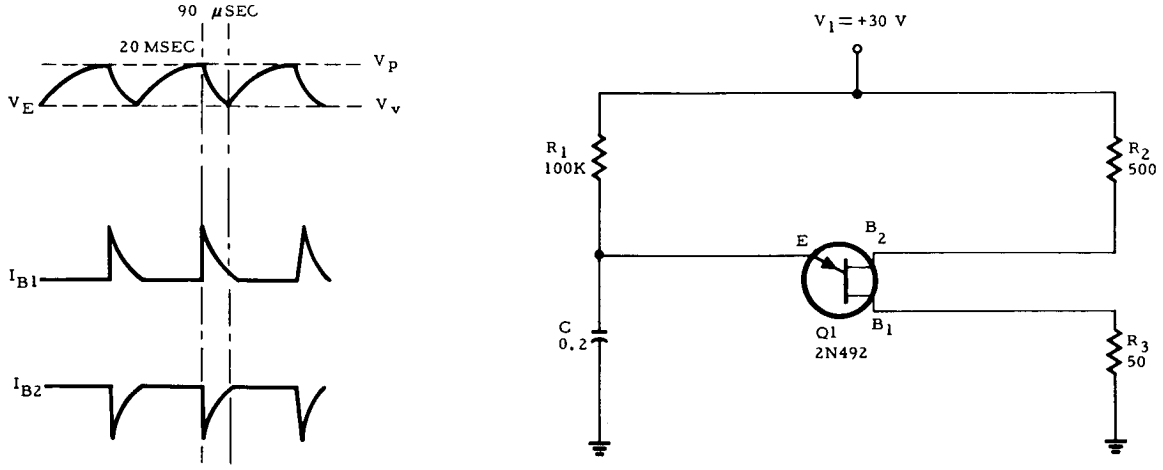


Figure B-23. Typical Unijunction Transistor Relaxation Oscillator

through R_1, V_E becomes slightly greater than V_P. With the I_E available from C greater than I_P (4 μ a), the transistor fires and C discharges through the E to B_1 resistance ($R_s \cong 40$ ohms) and R_3.

This situation is illustrated in Figure B-24. The transistor fires at point 1, at which time the emitter characteristics jump to the next stable operating point (2, theoretically the intersection of the peak voltage point and the saturation curve). From this point, capacitor C discharges through R_s along the saturation curve until V_E drops below the level required to maintain conduction (point 3, $V_V \cong 2$ v). When V_E drops below V_V, the emitter characteristics revert to the cut-off state (point 4) and the cycle is repeated. Because very little current is contributed by V_1 acting through R_1, the effective $I_{E(MAX)}$ is contributed by C. The effective resistance reduction between E and B_1 causes an increased I_{B2} which appears as a current gain relative to I_E through R_3. Because this circuit requires analysis at the point of maximum emitter current, the equivalent circuit of Figure B-25 can be used.

The emitter branch is represented as a diode with R_s equal to the emitter saturation resistance (about 40 ohms) and V_O equal to the voltage intercept of the saturation curve extension (1.5 v opposed to emitter current). Maximum emitter current ($I_{E(MAX)}$) is limited by maximum current available from the capacitor (I_C). This value can be found using the relationship

$$I_{E(MAX)} = \frac{V_P - V_O}{R_S + R_3} ,$$

which, for the relaxation oscillator circuit of Figure B-23 is 182 ma.

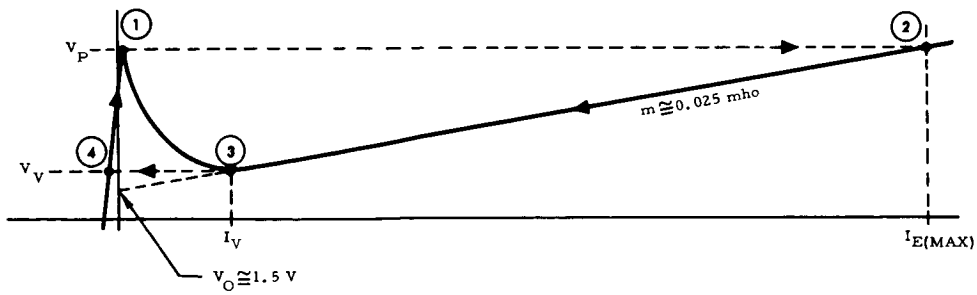


Figure B-24. Approximate Dynamic Emitter Characteristics of a Unijunction Transistor Used in a Relaxation Oscillator Circuit

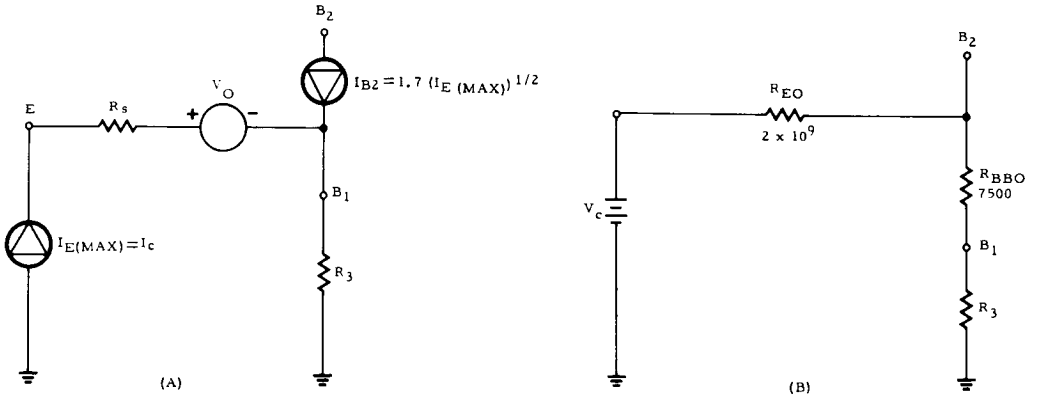


Figure B-25. Saturated (A) and Cut-Off (B) Unijunction

Hence, capacitor C is represented as an infinite impedance current generator in the equivalent circuit. The current-gain characteristic of the interbase transistor branch is approximated by infinite impedance constant-current generator I_{B2}. For the 2N492 unijunction transistor, the current produced by I_{B2} is calculated using the following empirically derived equation:

$$I_{B2(MAX)} = \frac{I_{B2\,(MOD)}}{7} (I_{E(MAX)})^{1/2}$$

where

$I_{B2(MOD)}$ is the nominal modulated interbase current from the 2N492 electrical characteristics shown in Table B-4,

$I_{E(MAX)}$ is calculated as above,

and

7 is the square root of I_E used to determine $I_{B2(MOD)}$ as specified in the electrical characteristics.

For this equivalent circuit, I_{B2} = 23 ma.

The cut-off equivalent circuit is shown in Figure B-25B, and is characterized by the emitter being reverse-biased with a large emitter-cutoff resistance (R_{EO}) and a relatively large interbase resistance (R_{BBO}). The value of R_{BBO} is obtained directly from the electrical characteristics of the transistor while R_{EO} is calculated from the characteristics, as follows:

Table B-4. Electrical Characteristics of the 2N492 Unijunction Transistor

CHARACTERISTIC	VALUE			UNIT
	MIN	NOM	MAX	
Major				
Interbase Resistance at $T_j = 25$ C (R_{BBO})	6200	7500	9100	ohm
Intrinsic Standoff Ratio (η)	0.56	0.62	0.68	—
Modulated Interbase Current at $I_E = 50$ ma, $V_{BB} = 10$ V ($I_{B2(MOD)}$)	6.8	12	22	ma
Emitter Reverse Current at $V_{EO} = 60$ V (I_{EO})	—	0.03	12	ua
Minor				
Emitter Saturation Voltage at $I_E = 50$ ma, $V_{BB} = 10$ V ($V_{E(SAT)}$)	2.7	3.6	4.5	V
Peak Point Emitter Current at $V_{BB} = 25$ V (I_p)	—	4	12	ua

$$R_{EO} = \frac{V_{EO}}{I_{EO}} = \frac{6 \times 10^{1}}{3 \times 10^{-8}} = 2 \times 10^{9} \text{ ohms.}$$

The capacitor is represented by battery V_C equal to V_V, the charge remaining at the point of cutoff (about 2.0 v).

Since a unijunction transistor jumps from the cut-off to saturated states and back to the cut-off state if enough emitter current is available, it is most likely that one of these two states will be encountered. For computer analysis, then, the unijunction transistor should be initially represented in the cut-off state and tests should be made for V_E. If $V_E < V_P$, the cut-off representation is valid and remains in the circuit. If, however, $V_E > V_P$, the transistor is operating in the saturation region and the saturated equivalent circuit must be substituted by the computer.

K. SPECIAL EQUIVALENT CIRCUITS

As mentioned previously, the equivalent circuits derived above are not catholic. The following is a description of a problem encountered in a circuit analysis and its solution.

A transistor operating in a circuit was discovered to have sufficient base current to put it in the saturated region. However, this transistor was operating as an inverted switch (I_C reversed) and the equivalent circuit of Figure B-15 for a saturated transistor was not valid. Because the collector current was reversed, the collector was behaving like an emitter, and R_{cx} was not required as a parameter.

If R_{cx} were removed from the circuit, a short would exist from the collector to emitter. Although not quite true, this assumption would be acceptable for some applications. The analysis of the circuit in which this situation arose required more accuracy than a collector-to-emitter short would allow.

Hence, it was decided to represent the collector and emitter as two emitters with two equal impedances: (1) contact resistance and (2) resistance of the transistor material as a function of the current through it. As shown in Figure B-26, the contact resistance (R_0) was set equal to 0.5 ohm, and the other impedance was found to be 0.026 v/I_E, where I_E is the d-c emitter current. This is equal to an 0.026 v generator opposing current flow in each emitter branch.

As can be seen from the foregoing example, equivalent circuits cannot be drawn to hard and fast rules. Therefore, to obviate the need for unnecessary work by an analyst, it is most desirable that the design engineer be the person who formulates or very closely supervises the development of the equivalent circuits for analysis.

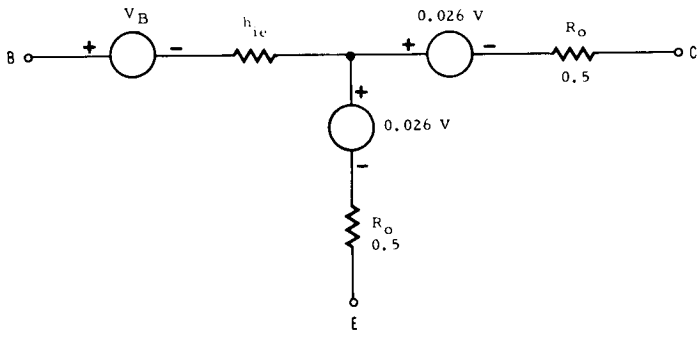


Figure B-26. D-C Equivalent Circuit of an Inverted Switch

L. D-C EQUIVALENT CIRCUIT OF THE SAMPLE CIRCUIT

Using the circuit-synthesis techniques described previously, the d-c equivalent circuit of Figure B-27 was developed for the sample circuit of Figure B-1.

Note that the 2N335A npn transistor is represented in the common emitter configuration operating in the active region with its parameters specified in converted common-base terms. The common emitter configuration is used because the real circuit uses it. The active region is assumed because the amplifier is supposed to operate without distorting the input signal. During the various analyses, tests will be conducted to ascertain whether or not the transistor will be driven into saturation or cut-off by variations in the circuit parameters or the input signal. Finally, the transistor common emitter parameters are stated in converted common-base terms so existing part data can be applied directly. This technique is in the nature of an experiment, because the conversions are being verified as this manual is written. Should they indeed be accurate, much empirical data gathering will be eliminated for future analyses.

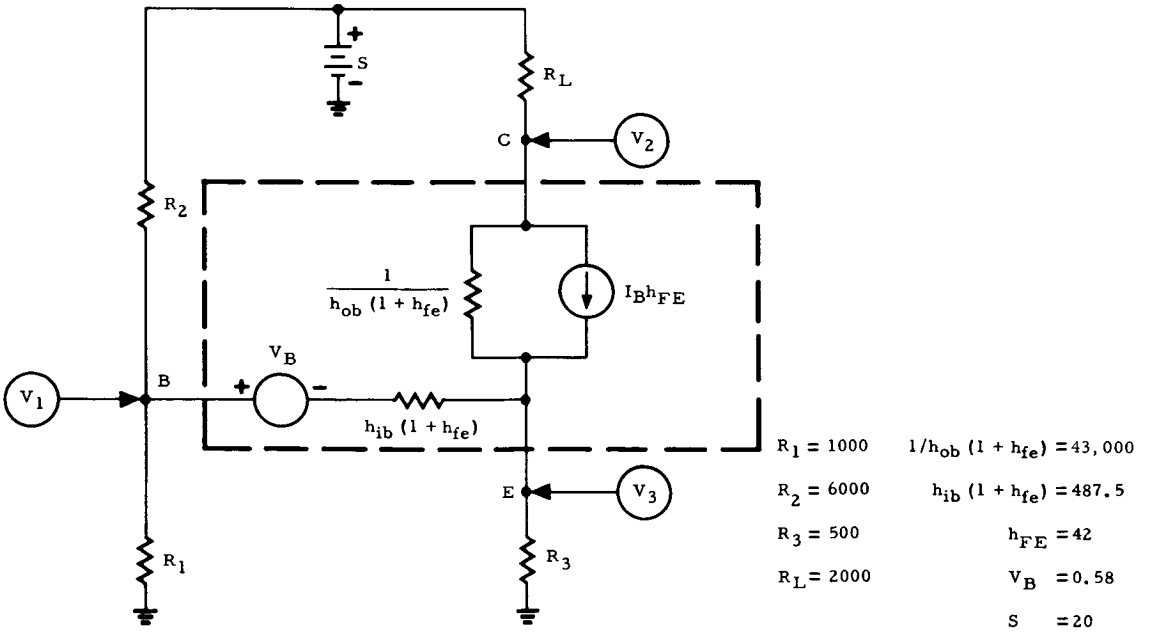


Figure B-27. D-C Equivalent Circuit of the Sample Circuit

For the circuit external to the transistor, all capacitors have been considered as open circuits because of the low voltages involved. Thus, the input and output loops are eliminated from consideration in the d-c equivalency. Nominal values for the resistors are equal to the precise values of the actual parts used in the breadboard model of the circuit that was constructed to verify the authenticity of the equivalent circuit. This was done so parameter variations would not have to be considered when comparing computed and measured nominal values.

Assuming the use of nonfailed parts, circuit operation is primarily dependent on the operation of the transistor. Thus, it is necessary to determine the currents through the transistor and the bias voltages applied to it. For these purposes, circuit equations for the equivalent circuit must be written. One of two methods can be used to determine the equations: (1) the loop-current method based on Kirchoff's voltage law, or (2) the node-voltage method based on Kirchoff's current law. For greatest simplicity, the node-voltage method is used to determine the equations for the d-c equivalent circuit of Figure B-27.

Essentially, Kirchoff's current law states that the algebraic sum of the currents at any branch point of a network is zero. Hence, the sum of the currents at each node-voltage point in Figure B-27 is zero (V_1, V_2, and V_3). Therefore,

$$\frac{V_1}{R_1} + \frac{V_1 - S}{R_2} + \frac{V_1 - V_B - V_3}{h_{ib}(1 + h_{fe})} = 0,$$

$$\frac{V_2 - S}{R_L} + \frac{V_2 - V_3}{1/h_{ob}(1 + h_{fe})} + \frac{(V_1 - V_B - V_3)\, h_{FE}}{h_{ib}(i + h_{fe})} = 0,$$

and

$$\frac{V_3}{R_3} + \frac{V_3 + V_B - V_1}{h_{ib}(1 + h_{fe})} + \frac{V_3 - V_2}{1/h_{ob}(1 + h_{fe})} - \frac{(V_1 - V_B - V_3)\, h_{FE}}{h_{ib}(1 + h_{fe})} = 0,$$

resulting in a system of three linear circuit equations in three unknown voltages whose coefficients are expressed in terms of known circuit

parameters. The third term in the second equation represents the current due to current generator $I_B\ h_{FE}$ because

$$I_B = \frac{V_1 - V_B - V_3}{h_{ib}\ (1 + h_{fe})}$$

from the first equation. The third term in the third equation is a negative $I_B\ h_{FE}$ because the direction of the current generator is opposed to the assumed current flow.

Rewriting the above system of equations as coefficients of the unknown node voltages results in the following system:

$$\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{h_{ib}\ (1 + h_{fe})}\right) V_1 + (0)\ V_2 - \left(\frac{1}{h_{ib}\ (1 + h_{fe})}\right) V_3 = \frac{S}{R_2} + \frac{V_B}{h_{ib}\ (1 + h_{fe})}$$

$$\left(\frac{h_{FE}}{h_{ib}\ (1 + h_{fe})}\right) V_1 + \left(\frac{1}{R_L} + h_{ob}\ (1 + h_{fe})\right) V_2 - \left(h_{ob}\ (1 + h_{fe}) + \frac{h_{FE}}{h_{ib}\ (1 + h_{fe})}\right) V_3 = \frac{S}{R_L} + \frac{V_B\ h_{FE}}{h_{ib}\ (1 + h_{fe})}$$

$$\left(\frac{1 + h_{FE}}{h_{ib}\ (1 + h_{fe})}\right) V_1 - \left(h_{ob}\ (1 + h_{fe})\right) V_2 + \left(\frac{1}{R_3} + \frac{1 + h_{FE}}{h_{ib}\ (+h_{fe})} + h_{ob}\ (1 + h_{fe})\right) V_3 = -V_B \left(\frac{1 + h_{FE}}{h_{ib}\ (1 + h_{fe})}\right)$$

These coefficients are used in the circuit-equation matrix of Table B-5. The figures directly below the coefficients are the computed nominal coefficient values using the parameters shown in Figure B-27 (in standard floating-point notation). When the computer solves this d-c matrix, voltages V_1, V_2, and V_3 will be known and are used to determine the quiescent operating point of the transistor and the stresses to which the circuit components are subjected.

M. EQUATIONS FOR A-C EQUIVALENT CIRCUITS

The a-c analysis of any circuit is somewhat more involved than its d-c analysis. This is due to the fact that complex quantities appear in the circuit equations because of the capacitive and/or inductive reactances. These quantities result in a system of 2n equations in 2n unknowns.

Table B-5. Matrix for the D-C Equivalent of the Sample Circuit

V_1	V_2	V_3	
$\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{h_{ib}(1+h_{fe})}$	0	$-\frac{1}{h_{ib}(1+h_{fe})}$	$\frac{V_B}{h_{ib}(1+h_{fe})} + \frac{S}{R_2}$
0.32179-02	0	-0.20513-02	0.45231-02
$\frac{h_{FE}}{h_{ib}(1+h_{fe})}$	$\frac{1}{R_L} + h_{ob}(1+h_{fe})$	$-h_{ob}(1+h_{fe}) - \frac{h_{FE}}{h_{ib}(1+h_{fe})}$	$\frac{S}{R_L} + \frac{V_B h_{FE}}{h_{ib}(1+h_{fe})}$
0.86154-01	0.52340-03	-0.86177-01	0.59969-01
$-\frac{1+h_{FE}}{h_{ib}(1+h_{fe})}$	$-h_{ob}(1+h_{fe})$	$\frac{1}{R_3} + \frac{1+h_{FE}}{h_{ib}(1+h_{fe})} + h_{ob}(1+h_{fe})$	$-\frac{V_B(1+h_{FE})}{h_{ib}(1+h_{fe})}$
-0.88205-01	-0.23400-04	0.90229-01	-0.51159-01

The system of n linear complex equations in n unknowns

$$(a_{11} + ib_{11})(x_1 + iy_1) + (a_{12} + ib_{12})(x_2 + iy_2) + \ldots + (a_{1n} + ib_{1n})(x_n + iy_n) = c_1 + id_1$$

$$(a_{21} + ib_{21})(x_1 + iy_1) + (a_{22} + ib_{22})(x_2 + iy_2) + \ldots + (a_{2n} + ib_{2n})(x_n + iy_n) = c_2 + id_2$$

$$\cdots \quad \cdots \quad \cdots \quad \cdots \quad \cdots$$
$$\cdots \quad \cdots \quad \cdots \quad \cdots \quad \cdots$$
$$\cdots \quad \cdots \quad \cdots \quad \cdots \quad \cdots$$

$$(a_{n1} + ib_{n1})(x_1 + iy_1) + (a_{n2} + ib_{n2})(x_2 + iy_2) + \ldots + (a_{nn} + ib_{nn})(x_n + iy_n) = c_n + id_n$$

where

a_{rs} is the real part of the coefficient matrix,

b_{rs} is the imaginary part of the coefficient matrix,

c_r is the real part of the dependent column vector,

d_r is the imaginary part of the dependent column vector,

x_s is the real part of the unknown vector,

y_s is the imaginary part of the unknown vector,

$r = 1, 2, 3, \ldots, n,$

and

$s = 1, 2, 3, \ldots, n,$

can be rewritten

$$a_{11} x_1 - b_{11} y_1 + ib_{11} x_1 + ia_{11} y_1 + \ldots a_{1n} x_n - b_{1n} y_n + ib_{1n} x_n + ia_{1n} y_n = c_1 + id_1$$

$$a_{21} x_1 - b_{21} y_1 + ib_{21} x_1 + ia_{21} y_1 + \ldots a_{2n} x_n - b_{2n} y_n + ib_{2n} x_n + ia_{2n} y_n = c_2 + id_2$$

$$\begin{array}{ccc} \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \end{array}$$

$$a_{n1} x_1 - b_{n1} y_1 + ib_{n1} x_1 + ia_{n1} y_1 + \ldots a_{nn} x_n - b_{nn} y_n + ib_{nn} x_n + ia_{nn} y_n = c_n + id_n$$

Each of the complex equations actually is two equations; the real terms on the left equal the real terms on the right, and the imaginary terms on the left equal the imaginary terms on the right. Treating each of the n equations as two equations, one real and one imaginary, the system becomes 2n real and imaginary equations in 2n unknowns, as follows:

$$\begin{cases} a_{11} x_1 + a_{12} x_2 + \ldots + a_{1n} x_n - b_{11} y_1 - b_{12} y_2 - \ldots - b_{1n} y_n = c_1 \\ ib_{11} x_1 + ib_{12} x_2 + \ldots + ib_{1n} x_n + ia_{11} y_1 + ia_{12} y_2 + \ldots + ia_{1n} y_n = id_1 \end{cases}$$

$$\begin{cases} a_{21} x_1 + a_{22} x_2 + \ldots + a_{2n} x_n - b_{21} y_1 - b_{22} y_2 - \ldots - b_{2n} y_n = c_2 \\ ib_{21} x_1 + ib_{22} x_2 + \ldots + ib_{2n} x_n + ia_{21} y_1 + ia_{22} y_2 + \ldots + ia_{2n} y_n = id_2 \end{cases}$$

$$\begin{array}{ccc} \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots \end{array}$$

$$\begin{cases} a_{n1} x_1 + a_{n2} x_2 + \ldots + a_{nn} x_n - b_{n1} y_1 - b_{n2} y_2 - \ldots - b_{nn} y_n = c_n \\ ib_{n1} x_1 + ib_{n2} x_2 + \ldots + ib_{nn} x_n + ia_{n1} y_1 + ia_{n2} y_2 + \ldots + ia_{nn} y_n = id_n \end{cases}$$

Multiplying both sides of each imaginary equation by i^{-1} and rearranging the system results in a final system of 2n real equations in 2n real unknowns

$$a_{11} x_1 + a_{12} x_2 + \cdots a_{1n} x_n - b_{11} y_1 - b_{12} y_2 - \cdots - b_{1n} y_n = c_1$$

$$a_{21} x_1 + a_{22} x_2 + \cdots a_{2n} x_n - b_{21} y_1 - b_{22} y_2 - \cdots - b_{2n} y_n = c_2$$

$$\cdots \qquad \cdots \qquad \cdots$$
$$\cdots \qquad \cdots \qquad \cdots$$
$$\cdots \qquad \cdots \qquad \cdots$$

$$a_{n1} x_1 + a_{n2} x_2 + \cdots a_{nn} x_n - b_{n1} y_1 - b_{n2} y_2 - \cdots - b_{nn} y_n = c_n$$

$$b_{11} x_1 + b_{12} x_2 + \cdots b_{1n} x_n + a_{11} y_1 + a_{12} y_2 + \cdots + a_{1n} y_n = d_1$$

$$b_{21} x_1 + b_{22} x_2 + \cdots b_{2n} x_n + a_{21} y_1 + a_{22} y_2 + \cdots + a_{2n} y_n = d_2$$

$$\cdots \qquad \cdots \qquad \cdots$$
$$\cdots \qquad \cdots \qquad \cdots$$
$$\cdots \qquad \cdots \qquad \cdots$$

$$b_{n1} x_1 + b_{n2} x_2 + \cdots b_{nn} x_n + a_{n1} y_1 + a_{n2} y_2 + \cdots + a_{nn} y_n = d_n$$

Schematically, the matrix for the above system is written

$$\left[\begin{array}{cc} +R_c & -I_c \\ \hline +I_c & +R_c \end{array}\right] \left[\begin{array}{c} X_v \\ \hline iX_v \end{array}\right] = \left[\begin{array}{c} +R_v \\ \hline +I_v \end{array}\right]$$

where

R_c is the real part of the coefficient matrix,

I_c is the imaginary part of the coefficient matrix,

X_v is the real part of the unknown vector,

iX_v is the imaginary part of the unknown vector,

R_v is the real part of the dependent column vector,

and I_v is the imaginary part of the dependent column vector.

N. A-C EQUIVALENT CIRCUIT OF THE SAMPLE CIRCUIT

The a-c equivalent circuit developed for the sample circuit of Figure B-1 is shown in Figure B-28. The nominal values of the resistances are the same as those in the d-c equivalent circuit (Figure B-27). Note that all d-c voltage sources have been eliminated and only the active-region transistor equivalency is used.

Input signal e_{in} and output impedance R_{out} are included in this circuit because capacitors C_1 and C_2 present finite impedance to the input and output signals. All capacitors are represented without their equivalent series resistances because these quantities were found to be insignificant for the application of the sample circuit. However, it is necessary to include transistor collector-to-emitter capacitance C_C.

The a-c equivalent-circuit system of three linear equations in three unknowns is presented in Table B-6. Based on the theorem of linear complex equations these equations are used to formulate the 6 x 6 matrix of Table B-7.

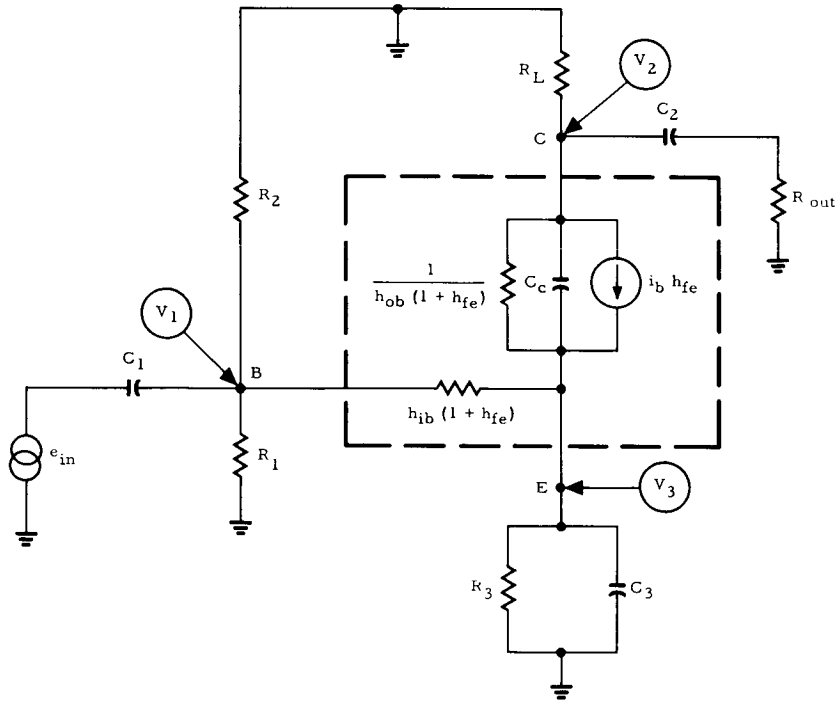


Figure B-28. A-C Equivalent Circuit of the Sample Circuit

Table B-6. Equations for the A-C Equivalent Sample Circuit

$$(1)\quad (V_1 - e_{in})\, j\,\omega C_1 + \frac{V_1}{R_1} + \frac{V_1 - V_3}{h_{ib}\,(1 + h_{fe})} + \frac{V_1}{R_2} = 0$$

$$(2)\quad \frac{V_2}{R_L} + \frac{V_2\,\omega C_2}{R_{out}\,\omega C_2 - j} + (V_2 - V_3)\left[h_{ob}\,(1 + h_{fe})\right] + (V_2 - V_3)\, j\,\omega C_c + \frac{(V_1 - V_3)h_{fe}}{h_{ib}\,(1 + h_{fe})} = 0$$

$$(3)\quad \frac{V_3}{R_3} + V_3 j\,\omega C_3 + \frac{V_3 - V_1}{h_{ib}\,(1 + h_{fe})} + (V_3 - V_2)\left[h_{ob}\,(1 + h_{fe}) + j\,\omega C_c\right] - \frac{(V_1 - V_3)h_{fe}}{h_{ib}\,(1 + h_{fe})} = 0$$

$$(1)\quad \left(j\,\omega C_1 + \frac{1}{R_1} + \frac{1}{h_{ib}\,(1 + h_{fe})} + \frac{1}{R_2}\right) V_1 + (0)\, V_2 - \left(\frac{1}{h_{ib}\,(1 + h_{fe})}\right) V_3 = e_{in}\, j\,\omega C_1$$

$$(2)\quad \left(\frac{h_{fe}}{h_{ib}\,(1 + h_{fe})}\right) V_1 + \left(\frac{1}{R_L} + \frac{\omega C_2}{R_{out}\,\omega C_2 - j} + h_{ob}\,(1 + h_{fe}) + j\,\omega C_c\right) V_2 - \left(h_{ob}\,(1 + h_{fe}) + j\,\omega C_c + \frac{h_{fe}}{h_{ib}\,(1 + h_{fe})}\right) V_3 = 0$$

$$(3)\quad \left(-\frac{1}{h_{ib}}\right) V_1 - \left(h_{ob}\,(1 + h_{fe}) + j\,\omega C_c\right) V_2 + \left(\frac{1}{R_3} + j\,\omega C_3 + \frac{1}{h_{ib}} + h_{ob}(1 + h_{fe}) + j\,\omega C_c\right) V_3 = 0$$

Table B-7. Matrix for the A-C Equivalent Sample Circuit Equations

V1R	V2R	V3R	V1I	V2I	V3I	
$\frac{1}{R_1} + \frac{1}{h_{ib}(1+h_{fe})} + \frac{1}{R_2}$ 0.32179-02	0 0	$\frac{-1}{h_{ib}(1+h_{fe})}$ -0.20513-02	$-\omega C_1$ -0.31416-01	0 0	0 0	0 0
$\frac{h_{fe}}{h_{ib}(1+h_{fe})}$ 0.77949-01	$\frac{1}{R_L} + \frac{(\omega C_2)^2 R_{OUT}}{(R_{out}\ \omega C_2)^2 + 1} + h_{ob}(1+h_{fe})$ 0.62340-03	$-h_{ob}(1+h_{fe}) - \frac{h_{fe}}{h_{ib}(1+h_{fe})}$ -0.77972-01	0 0	$\frac{-\omega C_2}{(R_{OUT}\ \omega C_2)^2 + 1} - \omega C_c$ -0.31831-06	ωC_c 0.50266-07	0 0
$-\frac{1}{h_{ib}}$ -0.80000-01	$-h_{ob}(1+h_{fe})$ -0.23400-04	$\frac{1}{R_3} + \frac{1}{h_{ib}} + h_{ob}(1+h_{fe})$ 0.82023-01	0 0	ωC_c 0.50266-07	$-\omega C_3 - \omega C_c$ -0.37699-00	0 0
ωC_1 0.31416-01	0 0	0 0	$\frac{1}{R_1} + \frac{1}{h_{ib}(1+h_{fe})} + \frac{1}{R_2}$ 0.32179-02	0 0	$\frac{-1}{h_{ib}(1+h_{fe})}$ -0.20513-02	$e_{in}\ \omega C_1$ 0.13352-02
0 0	$\frac{\omega C_2}{(R_{out}\ \omega C_2)^2 + 1} + \omega C_c$ 0.31831-06	$-\omega C_c$ -0.50266-07	$\frac{h_{fe}}{h_{ib}(1+h_{fe})}$ 0.77949-01	$\frac{1}{R_L} + \frac{(\omega C_2)^2 R_{OUT}}{(R_{OUT}\ \omega C_2)^2 + 1} + h_{ob}(1+h_{fe})$ 0.62340-03	$-h_{ob}(1+h_{fe}) - \frac{h_{fe}}{h_{ib}(1+h_{fe})}$ -0.77972-01	0 0
0 0	$-\omega C_c$ -0.50266-07	$\omega C_3 + \omega C_c$ 0.37699-00	$-\frac{1}{h_{ib}}$ -0.80000-01	$-h_{ob}(1+h_{fe})$ -0.23400-04	$\frac{1}{R_3} + \frac{1}{h_{ib}} + h_{ob}(1+hfe)$ 0.82023-01	0 0

O. SAMPLE CIRCUIT ANALYSIS

In drawing the d-c and a-c equivalent circuits of the sample circuit shown in Figure B-1, and writing equivalent circuit equations in terms of the input parameters, the first two steps in the initial phase of the complete analysis are accomplished. A breadboard model of the sample circuit was constructed and laboratory tests were performed thereon. The accuracy of the equations was verified by solving the equations at nominal parameter values and comparing the solutions with the data obtained from the laboratory tests on the breadboard model.

In the two equivalent circuits, 17 input parameters are represented. Each of these parameters is assigned an input parameter number as shown in Table B-8. Note that the parameter symbols in the equivalent circuits and the computer printouts differ slightly. This is due to the fact that the digital computer can print out only upper-case letters. The output parameters to be investigated are shown in Table B-9.

As each method of analysis is explained in the following sections, the equations developed above will be incorporated into the computer program and the circuit deficiencies will show up in the computer printout. To assure a thorough understanding of the analysis results, the circuit failures and the computer-indicated causes for it will be pointed out.

Table B-8. Sample Circuit Input Parameters

PARAMETER SYMBOL		NOMINAL VALUE	UNIT	INPUT PARAMETER NUMBER	NOMINAL VALUE, FLOATING POINT NOTATION
EQ CKT	COMPUTER				
R_1	R1	1000	ohm	1	0.10000 04
R_2	R2	6000	ohm	2	0.60000 04
R_3	R3	500	ohm	3	0.50000 03
R_L	RL	2000	ohm	4	0.20000 04
** R_{out}	ROUT	10000	ohm	5 **	0.10000 05
** C_1	C1	5	uf	6 **	0.50000 - 05
** C_2	C2	5	uf	7 **	0.50000 - 05
** C_3	C3	60	uf	8 **	0.60000 - 04
** C_c.	CC	8	uuf	9 **	0.80000 - 11
* h_{FE}	HFED	42	-	10 *	0.42000 02
h_{fe}	HFEA	38	-	11	0.38000 02
h_{ib}	HIB	12.5	ohm	12	0.12500 02
h_{ob}	HOB	0.6	umho	13	0.60000 - 06
** f	F	1000	cps	14 **	0.10000 04
* S	S	20	V	15 *	0.20000 02
** e_{in}	EIN	42.5	mv (peak)	16 **	0.42500 - 01
* V_B	VBE	0.58	V	17 *	0.58000 00

* D-C Matrix Only
** A-C Matrix Only

Table B-9. Sample Circuit Output Parameters

OUTPUT PARAMETER		DEFINITION
NUMBER	SYMBOL	
1	RL1	Real part of V_1 A-C Voltage
2	RL2	Real part of V_2 A-C Voltage
3	RL3	Real part of V_3 A-C Voltage
4	IM1	Imaginary part of V_1 A-C Voltage
5	IM2	Imaginary part of V_2 A-C Voltage
6	IM3	Imaginary part of V_3 A-C Voltage
7	DC1	V_1 D-C Voltage
8	DC2	V_2 D-C Voltage
9	DC3	V_3 D-C Voltage
10	PR1	Power Dissipated by R_1
11	PR2	Power Dissipated by R_2
12	PR3	Power Dissipated by R_3
13	PRL	Power Dissipated by R_L
14	PTC	Power Dissipated by Transistor Collector
15	STV	Transistor Collector-to-Emitter D-C Voltage
16	COV	Transistor Base-to-Emitter Instantaneous Voltage
17	PHS	Transistor Phase Shift
18	V1M	V_1 A-C Peak Node Voltage $(RL1^2 + IM1^2)^{1/2}$
19	V1PH	V_1 Phase Angle
20	V2M	V_2 A-C Peak Node Voltage $(RL2^2 + IM2^2)^{1/2}$
21	V2PH	V_2 Phase Angle
22	V3M	V_3 A-C Peak Node Voltage $(RL3^2 + IM3^2)^{1/2}$
23	V3PH	V_3 Phase Angle

MANDEX WORST-CASE ANALYSIS

A. INTRODUCTION

The Mandex (Modified and Expanded) Worst-Case Analysis Program is a method for doing a worst-case analysis of a circuit wherein the computer (1) calculates the partial derivatives of the output variables (power dissipations, voltages, etc) with respect to the input parameters (part values, input voltages, etc); (2) determines how to set the input parameters to obtain the worst-case solutions for the output variables from the sign of the partials; and (3) solves for the worst-case values of the output variables. Additionally, certain other calculations are performed to provide the designer with information on the effects of varying the input parameter values.

B. MANDEX ANALYSIS PRINTOUT SHEETS

The printout sheets for a Mandex analysis are divided into six sections: (1) Input Parameter Data, (2) Output Variable Test Information, (3) Nominal Solutions, (4) Detailed Mandex Results, (5) One-at-a-time Output Variable Solutions, and (6) Summary.

Input Parameter Data

Table B-10 is the Input Parameter Data section of the sample circuit analysis printout. The name of the circuit analyzed is given in the section title and written into the computer program circuit subroutine. Next, the number of input parameters and output variables is listed. Beneath this preliminary data are listed the input parameter symbols, numbers, nominal and extreme values, and nominal to extreme value percent changes. The input parameter values are listed in standard floating-point notation while the percent changes are listed in fixed-point form. The symbols, numbers, nominal values, and percent changes are entered into the computer as part of the input data.

Output Variable Test Information

Table B-11 is the Output Variable Test Information section of the sample circuit analysis printout. This section lists the name of the

Table B-10. Mandex Worst-Case Input Parameter Data

NUMBER OF INPUT PARAMETERS = 17 NUMBER OF OUTPUT VARIABLES = 23

SYMBOL	NUMBER	NOMINAL	NUMERICAL VALUE MAX	MIN	PERCENT CHANGE MAX	MIN
R1	1	0.10000E 04	0.10600E 04	0.92000E 03	6.0000	8.0000
R2	2	0.60000E 04	0.63600E 04	0.55200E 04	6.0000	8.0000
R3	3	0.50000E 03	0.53000E 03	0.46000E 03	6.0000	8.0000
RL	4	0.20000E 04	0.21200E 04	0.18400E 04	6.0000	8.0000
ROUT	5	0.10000E 05	0.10600E 05	0.92000E 04	6.0000	8.0000
C1	6	0.50000E-05	0.60000E-05	0.40000E-05	20.0000	20.0000
C2	7	0.50000E-05	0.60000E-05	0.40000E-05	20.0000	20.0000
C3	8	0.60000E-04	0.72000E-04	0.48000E-04	20.0000	20.0000
CC	9	0.80000E-11	0.20000E-10	0.40000E-11	150.0000	50.0000
HFED	10	0.42000E 02	0.84000E 02	0.10500E 02	100.0000	75.0000
HFEA	11	0.38000E 02	0.11400E 03	0.19000E 02	200.0000	50.0000
HI8	12	0.12500E 02	0.25000E 02	0.75000E 01	100.0000	40.0000
HO8	13	0.60000E-06	0.78000E-05	0.30000E-06	1200.0000	50.0000
F	14	0.10000E 04	0.10300E 04	0.97000E 03	3.0000	3.0000
S	15	0.20000E 02	0.21000E 02	0.19000E 02	5.0000	5.0000
EIN	16	0.42500E-01	0.46495E-01	0.38505E-01	9.4000	9.4000
WBE	17	0.58000E 00	0.58000E 00	0.58000E 00	0.	0.

Table B-11. Mandex Worst-Case Output Variable Test Information

OUTPUT VARIABLE TEST INFORMATION
TRAINING REPORT CIRCUIT ANALYSIS

SYMBOL	NUMBER	MAX TEST VALUE	MIN TEST VALUE	TEST
RL1	1	-0.10000E 04	0.10000E 04	BOTH
RL2	2	-0.10000E 04	0.10000E 04	BOTH
RL3	3	-0.10000E 04	0.10000E 04	BOTH
IM1	4	-0.10000E 04	0.10000E 04	BOTH
IM2	5	-0.10000E 04	0.10000E 04	BOTH
IM3	6	-0.10000E 04	0.10000E 04	BOTH
DC1	7	-0.10000E 04	0.10000E 04	BOTH
DC2	8	-0.10000E 04	0.10000E 04	BOTH
DC3	9	-0.10000E 04	0.10000E 04	BOTH
PR1	10	1.00000E-01	-0.	MAX
PR2	11	1.00000E-01	-0.	MAX
PR3	12	1.00000E-01	-0.	MAX
PRL	13	1.00000E-01	-0.	MAX
PTC	14	0.28000E-00	-0.	MAX
STV	15	0.	0.10000E 01	MIN
COV	16	0.	0.	MAX
PHS	17	0.17500E 03	0.16500E 03	BOTH
VIM	18	-0.10000E 04	0.10000E 04	BOTH
V1PH	19	-0.10000E 04	0.10000E 04	BOTH
V2M	20	0.60000E 01	0.40000E 01	BOTH
V2PH	21	-0.10000E 04	0.10000E 04	BOTH
V3M	22	-0.10000E 04	0.10000E 04	BOTH
V3PH	23	-0.10000E 04	0.10000E 04	BOTH

circuit analyzed under the section title together with the symbols and numbers of the output variables, the maximum and/or minimum values with which the worst-case solutions are compared, and information as to whether the output variables are tested for maximum or minimum, or both.

Both this section and the Input Parameter Data section consists primarily of information supplied to the computer. In addition to providing reference information for the analysis results, printing out this data serves as a check to verify that the computer has received the correct information.

Nominal Solutions

Table B-12 shows the sample circuit a-c nominal matrix, the d-c nominal matrix, and the output variable solutions for all input parameter values set at their nominal values. The matrices are listed in rows in floating-point notation with six elements per line:

The 6 x 6 a-c matrix

H(1, 1)	H(1, 2)	H(1, 3)	H(1, 4)	H(1, 5)	H(1. 6)
H(2, 1)	H(2, 2)	H(2, 3)	H(2, 4)	H(2, 5)	H(2, 6)
H(3, 1)	H(3, 3)	H(3, 4)	H(3, 5)	H(3, 5)	H(3. 6)
H(4, 1)	H(4, 2)	H(4, 3)	H(4, 4)	H(4, 5)	H(4, 6)
H(5, 1)	H(5, 2)	H(5, 3)	H(5, 4)	H(5, 5)	H(5, 6)
H(6, 1)	H(6, 2)	H(6, 3)	H(6, 4)	H(6, 5)	H(6, 6)
T(1)	H(2)	T(3)	T(4)	T(5)	T(6)

The 3 x 3 d-c matrix

H(1, 1)	H(1, 2)	H(1, 3)	H(2, 1)	H(2, 2)	H(2, 3)
H(3, 1)	H(3, 2)	H(3, 3)	T(1)	T(2)	T(3)

Table B-12. Mandex Worst-Case Nominal Solutions for Output Variables

NOMINAL MATRIX (6 x 6 a-c matrix)

0.32179E-02	0.	-0.20513E-02	-0.31416E-01	0.	0.
0.77949E-01	0.62340E-03	-0.77972E-01	0.	-0.31831E-06	0.50266E-07
-0.80000E-01	-0.23400E-04	0.82023E-01	0.	0.50266E-07	-0.37699E-00
0.31416E-01	-0.	-0.	0.32179E-02	0.	-0.20513E-02
-0.	0.31831E-06	-0.50266E-07	0.77949E-01	0.62340E-03	-0.77972E-01
-0.	-0.50266E-07	0.37699E-00	-0.80000E-01	-0.23400E-04	0.82023E-01
0.	0.	0.	0.13352E-02	0.	0.

NOMINAL MATRIX (3 x 3 d-c matrix)

0.32179E-02	0.	-0.20513E-02	0.90154E-01	0.52340E-03	-0.86177E-01
-0.88205E-01	-0.23400E-04	0.90229E-01	0.45231E-02	0.59969E-01	-0.51159E-01

NOMINAL SOLUTIONS FOR OUTPUT VARIABLES

0.41560E-01	-0.48836E 01	0.25087E-02	0.40932E-02	-0.15062E 01	-0.79706E-02
0.27758E 01	0.11591E 02	0.21496E 01	0.78701E-02	0.49276E-01	0.92925E-02
0.11496E-01	0.92435E-01	0.43309E 01	-0.53039E-02	0.16848E 03	0.41761E-01
0.56249E 01	0.51106E 01	0.19714E 03	0.83561E-02	0.28747E 03	

Similarly, the 23 nominal output variable solutions are listed in rows in floating-point notation with six elements per line (OV = output variable):

OV 1	OV 2	OV 3	OV 4	OV 5	OV 6
OV 7	OV 8	OV 9	OV 10	OV 11	OV 12
OV 13	OV 14	OV 15	OV 16	OV 17	OV 18
OV 19	OV 20	OV 21	OV 22	OV 23	

Detailed Mandex Results

Tables B-13 and B-14 show the detailed Mandex results for output variable 17 (PHS) of the sample circuit tested at worst-case maximum and worst-case minimum, respectively. In the complete sample circuit Mandex printout, similar sheets were prepared for each output variable solution. As shown in Table B-11, the sample circuit had 16 output variables tested for both maximum and minimum values, six for maximum, and one for minimum. Thus, the complete Detailed Mandex Results section for the sample circuit consisted of 39 sheets similar to Tables B-13 and B-14.

As shown in Table B-13, the allowed maximum value (see column MAX TEST VALUE) was 175 degrees while the worst-case solution (see column SOLUTION VALUE) was 178 degrees. Hence, the solution value failed the worst-case requirement by 3 degrees (see column DIFFERENCE).

The O under column EQU CKT CHECK indicates that the equivalent circuit used was valid. A 1 or a 2 here would have meant that the transistor either saturated or cut off and that a saturated or cut-off equivalent circuit would have to be used for valid results.

The 1 under column LOGIC STATE indicates that the active-region equivalent circuit was used to obtain the values on the page. If a matrix change was required as indicated under column EQU CKT CHECK, and special logic was written into the circuit subroutine covering the change, the number under column LOGIC STATE would indicate the change.

Table B-13. Mandex Worst-Case Information for Output Variable *
No. 17 (PHS), Worst-Case Maximum

MAX TEST VALUE	SOLUTION VALUE	DIFFERENCE	EQU CKT CHECK	LOGIC STATE
0.17500E 03	0.17804E 03	0.3042E 01.	0.	1

WORST CASE REQUIREMENT FAILED

	INPUT	PARAMETERS			OUTPUT CHANGE	PERCENT	PARTIAL TIMES	LINEARITY	EQ CKT
SYM.	NO.	NOMINAL	MAX WORST CASE	PARTIAL	FROM NOMINAL	CHANGES	INPUT CHANGE	CHECK	TEST
R1	1	0.1000E 04	0.1060E 04	0.7629E-07	0.1907E-05	0.000	0.4578E-05	-0.267E-05	0.
R2	2	0.6000E 04	0.5520E 04	-0.5147E-08	0.1907E-05	0.000	0.2470E-05	-0.563E-06	0.
R3	3	0.5000E 03	0.4600E 03	-0.2557E-04	0.1116E-02	0.009	0.1023E-02	0.930E-04	0.
RL	4	0.2000E 04	0.2120E 04	0.1828E-03	0.2165E-01	0.179	0.2191E-01	-0.259E-03	0.
ROUT	5	0.1000E 05	0.1060E 05	0.1429E-05	0.9174E-03	0.008	0.8572E-03	0.602E-04	0.
C1	6	0.5000E-05	0.4000E-05	-0.2906E 02	0.	0.	0.2906E-04	-0.291E-04	0.
C2	7	0.5000E-05	0.4000E-05	-0.5858E 04	0.7326E-02	0.061	0.5858E-02	0.147E-02	0.
C3	8	0.6000E-04	0.7200E-04	0.1868E 06	0.1881E 01	15.548	0.2242E 01	-0.361E-00	0.
CC	9	0.8000E-11	0.4000E-11	-0.3860E 07	0.9727E-04	0.001	0.1544E-04	0.818E-04	0.
HFED	10	0.4200E 02	0.4200E 02	0.	0.	0.	0.	0.	0.
HFEA	11	0.3800E 02	0.1140E 03	0.1070E-01	0.7592E 00	6.274	0.8129E 00	-0.537E-01	0.
HIB	12	0.1250E 02	0.2500E 02	0.8976E 00	0.5709E 01	47.180	0.1122E 02	-0.551E 01	0.
HOB	13	0.6000E-06	0.7800E-05	0.6763E 06	0.3394E 01	28.046	0.4869E 01	-0.148E 01	2.
F	14	0.1000E 04	0.1030E 04	0.1118E-01	0.3261E-00	2.695	0.3354E-00	-0.936E-02	0.
S	15	0.2000E 02	0.2000E 02	0.	0.	0.	0.	0.	0.
EIN	16	0.4250E-01	0.4250E-01	0.	0.	0.	0.	0.	0.
VBE	17	0.5800E 00	0.5800E 00	0.	0.	0.	0.	0.	0.
			SUMMATIONS		0.1210E 02		0.1951E 02		

WORST CASE SOLUTION MINUS NOMINAL SOLUTION FOR OUTPUT VARIABLE NO. 17 - PHS - 0.9558E 01

SOLUTIONS FOR ALL OUTPUT VARIABLES WITH OUTPUT VARIABLE NO. 17 - PHS - TESTED FOR WORST CASE MAX

0.42344E-01	-0.11439E 01	0.13699E-03	0.24066E-02	-0.10432E-00	-0.14203E-02	0.32084E 01	0.81202E 01
0.25847E 01	0.98934E-02	0.50897E-01	0.14534E-01	0.57779E-01	0.49541E-01	0.43869E 01	-0.13121E-02
0.17804E 03	0.42412E-01	0.32529E 01	0.11466E 01	0.19[illegible]E 02	0.14268E-02	0.27551E 03	

*The order of this output data is explained at the top of page B-51.

Table B-14. Mandex Worst-Case Information for Output Variable No. 17 (PHS), Worst-Case Minimum

MIN TEST VALUE	SOLUTION VALUE	DIFFERENCE	EQU CKT CHECK	LOGIC STATE
0.16500E 03	0.15577E 03	0.9226E 01	2.	1

WORST CASE REQUIREMENT FAILED

SYM.	INPUT NO.	PARAMETERS NOMINAL	WORST CASE MAX	PARTIAL	OUTPUT CHANGE FROM NOMINAL	PERCENT CHANGES	PARTIAL TIMES INPUT CHANGE	LINEARITY CHECK	EQUCKT TEST
R1	1	0.1000E 04	0.9200E 03	0.7629E-07	0.	0.	-0.6104E-05	-0.610E-05	0.
R2	2	0.6000E 04	0.6360E 04	-0.5147E-08	0.	0.	-0.1853E-05	-0.185E-05	0.
R3	3	0.5000E 03	0.5300E 03	-0.2557E-04	-0.7229E-03	-0.007	-0.7671E-03	-0.442E-04	0.
RL	4	0.2000E 04	0.1840E 04	0.1828E-03	-0.2968E-01	-0.275	-0.2922E-01	0.461E-03	0.
ROUT	5	0.1000E 05	0.9200E 04	0.1429E-05	-0.1019E-02	-0.009	-0.1143E-02	-0.124E-03	0.
C1	6	0.5000E-05	0.6000E-05	-0.2906E 02	0.1907E-05	100.000	-0.2906E-04	-0.310E-04	0.
C2	7	0.5000E-05	0.6000E-05	-0.5858E 04	-0.4883E-02	-0.045	-0.5858E-02	-0.975E-03	0.
C3	8	0.6000E-04	0.4800E-04	0.1868E 06	-0.2770E 01	-25.633	-0.2242E 01	0.528E 00	0.
CC	9	0.8000E-11	0.2000E-10	-0.3860E 07	-0.2861E-03	-0.003	-0.4632E-04	0.240E-03	0.
HFED	10	0.4200E 02	0.4200E 02	0.	0.	0.	0.	0.	0.
HFEA	11	0.3800E 02	0.1900E 02	0.1070E-01	-0.2068E-00	-1.913	-0.2032E-00	0.353E-02	2.
HIB	12	0.1250E 02	0.7500E 01	0.8976E 00	-0.7242E 01	-67.008	-0.4488E 01	0.275E 01	2.
HOB	13	0.6000E-06	0.3000E-06	0.6763E 06	-0.2065E-00	-1.911	-0.2029E-00	0.367E-02	0.
F	14	0.1000E 04	0.9700E 03	0.1118E-01	-0.3453E-00	-3.195	-0.3354E-00	0.991E-02	0.
S	15	0.2000E 02	0.2000E 02	0.	0.	0.	0.	0.	0.
EIN	16	0.4250E-01	0.4250E-01	0.	0.	0.	0.	0.	0.
VBE	17	0.5800E 00	0.5800E 00	0.	0.	0.	0.	0.	0.
			SUMMATIONS		-0.1081E 02		-0.7509E 01		

WORST CASE SOLUTION MINUS NOMINAL SOLUTION FOR OUTPUT VARIABLE NO. 17 - PHS - -0.1271E 02

SOLUTIONS FOR ALL OUTPUT VARIABLES WITH OUTPUT VARIABLE NO. 17 - PHS - TESTED FOR WORST CASE MIN

0.38630E-01	-0.56831E 01	0.91096E-02	0.66962E-02	-0.38419E 01	-0.13281E-01	0.24628E 01	0.13653E 02
0.18708E 01	0.67422E-02	0.48205E-01	0.66839E-02	0.12163E-02	0.12365E-00	0.49226E 01	0.23578E-01
0.15577E 03	0.39206E-01	0.98340E 01	0.68599E 01	0.21406E 03	0.16105E-01	0.30445E 03	

The third and fourth columns show the nominal values of the input parameters and the worst case values at which the input parameters were set to give a worst-case solution for the particular output variable. The fifth column lists the partial derivatives of the output variable with respect to each of the input parameters. Next are the changes in the output variable from nominal when each input parameter is moved from its nominal value to its worst-case values, while the other input parameters are held at their nominal values. Summing changes of the same sign and calculating percent changes produces the seventh column. The PERCENT CHANGES column gives an indication as to which input parameters are important to the variation of the output variable being tested for worst case. Ideally, the values in the PERCENT CHANGES column would all be of the same sign; plus when testing for a maximum value worst-case solution and minus when testing for a minimum value worst-case solution. However, because a point of inflection may occur in the input-output curve, there can be cases in which setting the input parameter in the direction indicated by the sign of the partial may produce a change in the output opposite to that desired. Experience with Mandex has shown that in every case where an input parameter was set to produce the wrong change in the output variable, the error in the result was negligible.

If the partial of an output variable with respect to an input parameter is a constant over the range of variation of the input parameter, the partial computed about the nominal value of the input parameter (or any other value of the input parameter within its range of variation) times the change of the input parameter is equal to the change in the output variable due to changing the input parameter. If the variation of the output variable with respect to an input parameter is linear, the partial of the output variable with respect to the input parameter is a constant. Therefore, the linearity of the input-output relationship can be investigated by comparing the partial times the input parameter change with the difference between the output variable solution when the input parameter is at nominal and the output variable solution when the input parameter is at its worst-case value. The LINEARITY CHECK column presents this comparison.

The last column, EQ CKT TEST, provides a check to see if the equivalent circuit success criteria are met when each of the input parameters is varied to its worst-case value.

An area of uncertainty that exists in the Mandex analysis technique is that of the effects that interrelationships of the input parameters may have on the output variables. For instance, if these effects were not present, the sum of the output changes from nominal, when the input parameters are varied one-at-a-time to their worst-case values, would equal the difference between the output variable solution with all input parameters at their worst-case values and the output variable solution with all input parameters at their nominal values. To provide an indication of the effects of interrelationships of the input parameters on the output variable, the above comparison is made. That is, the sum of the OUTPUT CHANGE FROM NOMINAL column (12.10) and the worst-case solution of the output variable minus the nominal solution of the output variable (9.558) are given for comparison. Also given is the sum of the PARTIAL TIMES INPUT CHANGE column (19.51). If the variations of the output variable with respect to all the input parameters were linear and there were no interrelationships of the input parameters, the three values would be equal. In practice, these quantities are probably never exactly equal. At the present state of development of Mandex, engineering judgement must be used to evaluate the above effects. The effects were not considered to be a problem in the example given.

The last item in the Detailed Mandex Results section is a list of the solutions of all output variables when one particular output variable is tested for a worst-case solution. The solutions are listed across the page in the standard floating-point notation.

One-at-a-Time Output Variable Solutions

Table B-15 shows the sample-circuit solutions for all output variables that are obtained for one-at-a-time variations of input parameters 1 through 4 at their worst-case values. The complete Mandex printout for the sample circuit included 26 more solutions, one each for the maximum and minimum worst-case values of all the input parameters. The one-at-a-time output variable solutions are obtained by:

1. Setting the first input parameter at its maximum worst-case value with all other input parameters at their nominal values

2. Computing the output variable values for condition 1

3. Setting the first input parameter at its minimum worst-case value with all other input parameters at their nominal values

4. Computing the output variable values for condition 3

5. Setting the second input parameter at its maximum worst-case value with all other input parameters at their nominal values

6. Computing the output variable values for condition 5

7. Continuing this procedure until the computer has set each input parameter at its maximum and minimum worst-case values with all other input parameters at their nominal values and the output variable values for each condition have been calculated

As shown in Table B-15, the output variable values are listed across the page in standard floating-point notation.

Summary

Because the Mandex analysis program results in a large volume of information, a section summarizing the analysis is included as part of the computer program. This summary is designed to be detached for inclusion in the report describing the Mandex circuit analysis.

The summary consists of (1) the circuit name and a listing of the input parameters and their variations allowed; (2) a comparison of the nominal solutions of the output variables with measured breadboard values; and (3) the Mandex Results, which contain a listing of the output variables, the limits against which solutions for these output variables were tested, the worst-case solutions for these output variables, an indication if the requirement was not met, an indication if the equivalent circuit was not valid, and the index numbers of input parameters which contribute more than 20 percent of the variation in a particular output variable.

Table B-15. Mandex Worst-Case Output Variable Solutions for One-at-a Time Input Parameter Variation

```
.INPUT PARAMETER NO.   1 -   R1 - AT MAX          LOGIC STATE= 1      EQU CKT CHECK= 0.
 0.41575E-01 -0.48871E 01  0.24950E-02  0.40207E-02 -0.14979E 01 -0.79764E-02  0.29115E 01  0.11074E 02
 0.22821E 01  0.81602E-02  0.48501E-01  0.10470E-01  0.14105E-01  0.91054E-01  0.36806E 01 -0.85335E-02
 0.16848E 03  0.41769E-01  0.55239E 01  0.51115E 01  0.19704E 03  0.83575E-02  0.28737E 03

 INPUT PARAMETER NO.   1 -   R1 - AT MIN          LOGIC STATE= 1      EQU CKT CHECK= 0.
 0.41575E-01 -0.48871E 01  0.24950E-02  0.40207E-02 -0.14979E 01 -0.79764E-02  0.29115E 01  0.11074E 02
 0.22821E 01  0.81602E-02  0.48501E-01  0.10470E-01  0.14105E-01  0.91054E-01  0.36806E 01 -0.85335E-02
 0.16848E 03  0.41769E-01  0.55239E 01  0.51115E 01  0.19704E 03  0.83575E-02  0.28737E 03

 INPUT PARAMETER NO.   2 -   R2 - AT MAX          LOGIC STATE= 1      EQU CKT CHECK= 0.
 0.41563E-01 -0.48842E 01  0.25064E-02  0.40811E-02 -0.15049E 01 -0.79716E-02  0.26410E 01  0.12105E 02
 0.20179E 01  0.71319E-02  0.47218E-01  0.81920E-02  0.91642E-02  0.93487E-01  0.49762E 01 -0.22061E-02
 0.16848E 03  0.41763E-01  0.56080E 01  0.51108E 01  0.19712E 03  0.83563E-02  0.28745E 03

 INPUT PARAMETER NO.   2 -   R2 - AT MIN          LOGIC STATE= 1      EQU CKT CHECK= 0.
 0.41563E-01 -0.48842E 01  0.25064E-02  0.40811E-02 -0.15049E 01 -0.79716E-02  0.26410E 01  0.12105E 02
 0.20179E 01  0.71319E-02  0.47218E-01  0.81920E-02  0.91642E-02  0.93487E-01  0.49762E 01 -0.22061E-02
 0.16848E 03  0.41763E-01  0.56080E 01  0.51108E 01  0.19712E 03  0.83563E-02  0.28745E 03

 INPUT PARAMETER NO.   3 -   R3 - AT MAX          LOGIC STATE= 1      EQU CKT CHECK= 0.
 0.41560E-01 -0.48839E 01  0.25065E-02  0.40934E-02 -0.15064E 01 -0.79718E-02  0.27806E 01  0.12039E 02
 0.21571E 01  0.78970E-02  0.49248E-01  0.88276E-02  0.94502E-02  0.92535E-01  0.47705E 01 -0.26461E-02
 0.16848E 03  0.41761E-01  0.56251E 01  0.51109E 01  0.19714E 03  0.83566E-02  0.28745E 03

 INPUT PARAMETER NO.   3 -   R3 - AT MIN          LOGIC STATE= 1      EQU CKT CHECK= 0.
 0.41560E-01 -0.48839E 01  0.25065E-02  0.40934E-02 -0.15064E 01 -0.79718E-02  0.27806E 01  0.12039E 02
 0.21571E 01  0.78970E-02  0.49248E-01  0.88276E-02  0.94502E-02  0.92535E-01  0.47705E 01 -0.26461E-02
 0.16848E 03  0.41761E-01  0.56251E 01  0.51109E 01  0.19714E 03  0.83566E-02  0.28745E 03

 INPUT PARAMETER NO.   4 -   RL - AT MAX          LOGIC STATE= 1      EQU CKT CHECK= 0.
 0.41561E-01 -0.51169E 01  0.25016E-02  0.40938E-02 -0.15762E 01 -0.79578E-02  0.27756E 01  0.11089E 02
 0.21493E 01  0.78689E-02  0.49277E-01  0.92895E-02  0.12391E-01  0.90142E-01  0.35852E 01 -0.54854E-02
 0.16851E 03  0.41762E-01  0.56255E 01  0.53542E 01  0.19712E 03  0.83418E-02  0.28745E 03

 INPUT PARAMETER NO.   4 -   RL - AT MIN          LOGIC STATE= 1      EQU CKT CHECK= 0.
 0.41561E-01 -0.51169E 01  0.25016E-02  0.40938E-02 -0.15762E 01 -0.79578E-02  0.27756E 01  0.11089E 02
 0.21493E 01  0.78689E-02  0.49277E-01  0.92895E-02  0.12391E-01  0.90142E-01  0.35852E 01 -0.54854E-02
 0.16851E 03  0.41762E-01  0.56255E 01  0.53542E 01  0.19712E 03  0.83418E-02  0.28745E 03
```

Part 1 of the summary is a repetition of section 1 of the Mandex analysis and was illustrated in Table B-10. The breadboard values for part 2 of the summary are entered into the computer as part of the input data. If a breadboard value is not available for an output variable, the value is entered as zero. A value, zero or otherwise, must be entered as breadboard data for all output variables, or else the comparison of computed values and breadboard data for output variables will not be made by the computer.

Table B-16 is the sample circuit Mandex Results part of the summary. This page summarizes the Detailed Mandex Results section of the analysis. The maximum and/or minimum values of the output variables that were tested for worst-case maximum or worst-case minimum are listed on the Mandex Results page.

These solution values, however, are the maximum and minimum values obtained during all of the calculations for the output variables. Therefore, they are not always the value calculated to be the worst-case value by valid use of the partials to set the input parameters. For example, the maximum value listed for RL2 MAX in Table B-16 is -0.98. The value given as the worst-case maximum in the Detailed Mandex Results section of the example analysis was -1.71. In the Mandex analyses that have been performed to date, it has been found that (1) discrepancies of the above nature were insignificant or (2) the equivalent circuit used for the analysis was not valid for that particular operating condition.

An aid is provided for use in determining cases in which the solution for an output variable appearing on the Mandex Results sheet is different from the solution value given as the worst-case value in the Detailed Mandex Results section. The number of the output variable which was being tested for worst case when the particular solution value printed on the Mandex Results sheet was obtained, is indicated in the last two columns of the sheet. The last two columns are not shown in Table B-16 because they are not intended to be included with a report on an analysis. Rather, they are given as an aid to the designer making the analysis and are printed out on the Tear-Off portion of the printout tapes.

C. SAMPLE CIRCUIT MANDEX WORST-CASE ANALYSIS

Table B-17 is a condensed table of the mathematical expressions given to the computer for the output variables and the worst-case values

Table B-16. Summary of Mandex Results

SYM.	NO.	TEST LIMITS MAX VALUE	TEST LIMITS MIN VALUE	SOLUTION VALUES MAX	SOLUTION VALUES MIN	CIRCUIT REQUIREMENT CHECK MAX	CIRCUIT REQUIREMENT CHECK MIN	PARAMETERS CONTRIBUTING MORE THAN 20 PERCENT OF OUTPUT VARIATION MAXIMUM	PARAMETERS CONTRIBUTING MORE THAN 20 PERCENT OF OUTPUT VARIATION MINIMUM
RL1	1	-0.10000E 04	0.10000E 04	EQ CKT FAIL	EQ CKT FAIL	'	'	' ' ' 16	' ' ' 16
RL2	2	-0.10000E 04	0.10000E 04	-0.98097E 00	EQ CKT FAIL	F	'	' ' 13 12	' ' ' 12
RL3	3	-0.10000E 04	0.10000E 04	EQ CKT FAIL	EQ CKT FAIL	'	'	' ' ' 12	' ' 13 12
IM1	4	-0.10000E 04	0.10000E 04	EQ CKT FAIL	0.14259E-02	'	F	' ' 12 11	' ' 12 11
IM2	5	-0.10000E 04	0.10000E 04	EQ CKT FAIL	EQ CKT FAIL	'	'	' ' 13 12	' ' ' 12
IM3	6	-0.10000E 04	0.10000E 04	-0.12857E-02	-0.16222E-01	F	F	' ' 13 12	' ' 12 8
DC1	7	-0.10000E 04	0.10000E 04	EQ CKT FAIL	0.21706E 01	'	F	' 15 2 1	15 10 2 1
DC2	8	-0.10000E 04	0.10000E 04	0.16488E 02	EQ CKT FAIL	F	'	' ' ' 10	' ' ' 2
DC3	9	-0.10000E 04	0.10000E 04	EQ CKT FAIL	0.11580E 01	'	F	' 15 2 1	' ' 10 1
PR1	10	1.00000E-01	-0.	EQ CKT FAIL	NOT TESTED	'	'	' ' 15 2	' ' ' '
PR2	11	1.00000E-01	-0.	0.60528E-01	NOT TESTED	'	'	' ' 15 2	' ' ' '
PR3	12	1.00000E-01	-0.	EQ CKT FAIL	NOT TESTED	'	'	' ' ' 2	' ' ' '
PRL	13	1.00000E-01	-0.	EQ CKT FAIL	NOT TESTED	'	'	' ' 13 12	' ' ' '
PTC	14	0.28000E-00	-0.	EQ CKT FAIL	NOT TESTED	'	'	' ' ' 13	' ' ' '
STV	15	0.	0.10000E 01	NOT TESTED	EQ CKT FAIL	'	'	' ' ' '	' ' ' 12
COV	16	0.	0.	EQ CKT FAIL	NOT TESTED	'	'	' 13 11 10	' ' ' '
PHS	17	0.17500E 03	0.16500E 03	0.17804E 03	EQ CKT FAIL	F	'	' ' 13 12	' ' 12 8
V1M	18	-0.10000E 04	0.10000E 04	EQ CKT FAIL	EQ CKT FAIL	'	'	' ' ' 16	' ' ' 16
V1PH	19	-0.10000E 04	0.10000E 04	EQ CKT FAIL	0.21260E 01	'	F	' 12 11 6	' ' 12 11
V2M	20	0.60000E 01	0.40000E 01	EQ CKT FAIL	0.98369E 00	'	F	' ' ' 12	' ' 13 12
V2PH	21	-0.10000E 04	0.10000E 04	EQ CKT FAIL	EQ CKT FAIL	'	'	' ' ' 12	' ' ' 12
V3M	22	-0.10000E 04	0.10000E 04	EQ CKT FAIL	EQ CKT FAIL	'	'	' ' 12 8	' ' 13 12
V3PH	23	-0.10000E 04	0.10000E 04	EQ CKT FAIL	EQ CKT FAIL	'	'	' ' ' 12	' ' ' 12

calculated by the computer. Normally, the worst-case values would be obtained from the Detailed Mandex Results section of the computer printout. The bulk of this section has been eliminated from this report to reduce its volume. Hence, the following comments will be referenced to Table B-17.

Output Parameters 1 Through 6

Output parameters 1 through 6 are the solutions to the 6 x 6 a-c matrix. Thus, the first three output parameters (RL1 through RL3) are the real parts of the a-c node voltages, and the second three are the imaginary parts. These parameters are used to compute output parameters 18 through 23.

Output Parameters 7 Through 9

Output parameters 7 through 9 are the d-c node voltages obtained by solving the 3 x 3 d-c matrix. The nominal values of DC1 through DC3 are used to check the validity of the equivalent circuit equations by comparing them with the values measured on the breadboard model.

Output Parameters 10 Through 13

Output parameters 10 through 13 are the power dissipated by R_1, R_2, R_3, and R_L, respectively. All resistors used in the circuit are rated at 0.1 w by their manufacturer. However, Apollo reliability policy requires that all resistors be derated 50 percent. Thus, for Apollo applications, the maximum allowable dissipation is 50 mw. It the circuit is to be used in applications where the resistors can be used at full power, the maximum allowable dissipation would be 100 mw.

The nominal power dissipated by R_1 is about 8 mw, and the maximum worst-case dissipation is 11 mw. Therefore, output parameter 10 is good even for Apollo applications.

The nominal power dissipated by R_2 is 49 mw, and the maximum worst-case dissipation is 61 mw. The worst-case value does not exceed the 100-mw resistor rating but it is more than the 50-percent derated limit. For Apollo application, a change to a resistor with a higher rating is indicated because the nominal value is very near the

Table B-17. Sample Circuit Mandex Worst-Case Analysis Output Parameter Equations and Calculated Values

OUTPUT PARAMETER		MATHEMATICAL EXPRESSION (OP = OUTPUT PARAMETER IP = INPUT PARAMETER)	COMPUTER DETERMINED VALUES			UNIT
SYMBOL	NUMBER		WORST-CASE MINIMUM	NOMINAL	WORST-CASE MAXIMUM	
RL1	1	*	0.0328	0.0416	0.0464	V
RL2	2	*	-9.29	-4.88	-1.71	V
RL3	3	*	0.0000979	0.00251	0.0105	V
IM1	4	*	0.00142	0.00409	0.0117	V
IM2	5	*	-5.12	-1.51	-0.0730	V
IM3	6	*	-0.0162	-0.00797	-0.00254	V
DC1	7	*	2.17	2.78	3.40	V
DC2	8	*	7.92	11.6	16.5	V
DC3	9	*	1.16	2.15	2.76	V
PR1	10	$\left\{\left[(OP1^2 + OP4^2)/2\right]^{\frac{1}{2}} + OP7\right\}^2/IP1$	—	0.00787	0.0111	W
PR2	11	$\left\{\left[(OP1^2 + OP4^2)/2\right]^{\frac{1}{2}} + OP7 - IP15\right\}^2/IP2$	—	0.0493	0.0605	W
PR3	12	$\left\{\left[(OP3^2 + OP6^2)/2\right]^{\frac{1}{2}} + OP9\right\}^2/IP3$	—	0.00929	0.0165	W
PRL	13	$\left\{\left[(OP2^2 + OP5^2)/2\right]^{\frac{1}{2}} + OP8 - IP15\right\}^2/IP4$	—	0.0115	0.0575	W
PTC	14	**		0.092	0.153	W
STV	15	$OP8-OP9 - \left\{(OP2-OP3)^2 + (OP5-OP6^2)\right\}^{\frac{1}{2}}$	-3.74	4.33	—	V
COV	16	$\left[(OP1-OP3)^2 + (OP4-OP6^2\right]^{\frac{1}{2}} - OP7+OP9+IP17$	—	-0.00536	0.0399	V
PHS	17	$\left\lvert \arctan OP4/OP1 - \arctan OP5/OP2 \right\rvert$	156.0	168.0	178.0	DEG
V1M	18	$(OP1^2 + OP4^2)^{\frac{1}{2}}$	0.0339	0.0418	0.0464	V
V1PH	19	$\arctan OP4/OP1$	2.13	5.62	16.3	DEG
V2M	20	$(OP2^2 + OP5^2)^{\frac{1}{2}}$	1.77	5.11	9.78	V
V2PH	21	$\arctan OP5/OP2$	184.0	197.0	218.0	DEG
V3M	22	$(OP3^2 + OP6^2)^{\frac{1}{2}}$	0.00129	0.00836	0.0176	V
V3PH	23	$\arctan OP6/OP3$	274.0	287.0	309.0	DEG

* OUTPUT PARAMETERS 1 THROUGH 9 DETERMINED DIRECTLY FROM MATRIX SOLUTIONS

** $$\left[\left(\frac{(OP2-OP3)^2 + (OP5-OP6)^2}{2}\right)^{\frac{1}{2}} + OP8-OP9\right]^2 IP13(1+IP11) +$$

$$\left[\left(\frac{(OP2-OP3)^2 + (OP5-OP6)^2}{2}\right)^{\frac{1}{2}} + OP8-OP9\right]\left(\frac{IP10\,(OP7-IP17-OP9)\,(2)^{\frac{1}{2}} + IP11\left[(OP1-OP3)^2 + (OP4-OP6)^2\right]^{\frac{1}{2}}}{IP12\,(1+IP11)\,(2)^{\frac{1}{2}}}\right)$$

derated limit, and the contribution to the output change from nominal is distributed among several parameters. (The Detailed Mandex Results printout for this parameter showed that input parameters 1, 2, 10, and 15 contributed 10, 29, 10, and 49 percent of the change in output parameter 11.)

The nominal power dissipated by R_3 is 9 mw, and the maximum worst-case dissipation is 16.5 mw; therefore, the 50-mw derated limit is not exceeded.

The nominal power dissipated by R_L is 11.5 mw, and the maximum worst-case dissipation is 57.5 mw. Also, the Detailed Mandex Results sheet for output parameter 13 showed that several input parameters contributed to the change with input parameter 2 (R_2) contributing the greatest amount (4 mw). Even if the contribution of R_2 could be reduced to zero by substituting a precision resistor (an impossibility), R_L still would dissipate 53.5 mw at worst-case conditions, necessitating other input parameter changes. Hence, the best solution would be to exchange R_L for a resistor with a higher power rating.

Output Parameter 14

The nominal power dissipated by the transistor collector is 92 mw, and the maximum worst-case dissipation is 153 mw. This does not exceed the rated collector dissipation characteristic of 280 mw, but does exceed the derated 140 mw limit. To be within the derated limit, the change from nominal must be limited to 48 mw rather than the present 61 mw deviation. This indicates that a 25-percent deviation reduction should be made. The Detailed Mandex Results sheet for output parameter 14 (PTC) showed the major contributors to the deviation were h_{ib}, S, and E_{in}. Limiting the variation from nominal of these input parameters by 40 percent should reduce the variation of PTC to less than 48 mw.

Output Parameters 15 and 16

Output parameter 15 (STV) is the transistor collector-to-emitter voltage drop, governing transistor saturation, and output parameter 16 (COV) is the base-to-emitter voltage drop, governing transistor cut-off. From the transistor collector characteristic curves, it can be seen that saturation will occur when V_{ce} (the d-c voltage minus the a-c voltage) drops below +1 v. The base-to-emitter voltage

(V_{be}, the a-c voltage minus the d-c voltage) must be negative or the base-to-emitter junction will be reverse biased, causing the transistor to cut off.

The nominal value of the collector voltage drop is 4.33 v and the worst-case value is -3.75 v. Since V_{ce} must be greater than +1, the allowable variation is 3.33 v. However, the worst-case variation is 8.08 v, indicating that the actual change from nominal must be reduced about 59 percent. This can be accomplished by greatly tightening most input parameter tolerances. Alternatively, the nominal value can be shifted up to 9.08 v by changing the bias resistors.

The nominal value of the base voltage drop is -5.4 mv, and the worst-case value is 39.9 mv Because V_{be} cannot exceed zero, the allowable variation is 5.4 mv However, the worst-case variation is 45.3 mv, indicating the actual change from nominal must be reduced about 88 percent. As with V_{ce}, this can be accomplished by greatly tightening most input parameter tolerances. Also, shifting the nominal value down to -45.3 mv by changing the bias resistors will eliminate the failure.

The most practical methods for correcting saturation and cut-off failures are to shift the bias points of the collector-to-emitter and base-to-emitter junctions. However, the collector-to-emitter bias must be shifted upward while the base-to-emitter bias must be shifted downward. Thus, if an adjustment is made to correct one failure, it will cause the other mean value to be nearer its failure point. It might even cause failure at the mean value. This indicates that the peak-to-peak input voltage is too high and either the input should be decreased or the circuit should be redesigned.

Output Parameter 17

The transistor phase shift (PHS) has a nominal value of 168.5 degrees, a maximum value of 178.0 degrees, and a minimum value of 155.8 degrees. The maximum and minimum test limits are 175 degrees and 165 degrees, respectively. Because this output variable is tested for both minimum and maximum, and because it fails at both limits, the input parameters must be adjusted until the worst-case value does not exceed either test value. With output variables tested at only one limit, it is possible to prevent the circuit from failing at the worst case by adjusting the mean value but allowing it to vary the same from the mean.

With output variable 17, it is necessary to restrict the variation from the mean as well as varying the mean.

It can be seen from the difference between the maximum test value and the worst-case maximum value that the phase shift has exceeded its maximum allowable by 3.04 degrees. The OUTPUT CHANGE FROM NOMINAL column states that restricting input parameters 12 and 13 by 50 percent will change the total output change from nominal by more then 3 degrees. To prevent the minimum test value from failing at the worst case, it will be necessary to restrict the variation of all of the input parameters by 80 to 90 percent. This is determined by comparing the difference between the minimum test value and the minimum worst-case value with the total change from nominal as shown by the worst-case solution minus the nominal solution. If the mean were shifted toward the midpoint between the minimum and maximum, away from the minimum value, it would place further restrictions on the input parameters to prevent a failure at the worst-case maximum, but it would decrease the restrictions on the parameters in the worst-case minimum direction. Assuming the mean of output variable 17 is adjusted to 170 degrees, change from nominal of 5 degrees in each direction can be allowed (a total change of 10 degrees). From the worst-case solution minus the nominal solution, output variable 17 varied 9.6 degrees in the maximum direction and 12.7 degrees in the minimum direction (a total of 22.3 degrees). From this and the total allowable variation of 10 degrees we can see that all of the input parameters must be restricted by more than 50 percent in each direction, or a failure will occur. This would indicate a circuit redesign or a widening of tolerance limits is necessary if the circuit is not to fail at worst case.

Output Parameter 18 Through 23

Output parameters 18, 20, and 22 are the a-c peak node voltages at V_1, V_2, and V_3, respectively, and output parameters 19, 21, and 23 are the respective phase angles associated with the peak node voltages.

From an output signal standpoint, output variable 20 (the output voltage) should be examined. The output voltage has a nominal value of 5.11 v, a worst-case maximum value of 9.78 v and a worst-case minimum value of 1.77 v. The maximum test limit is 6 v and the minimum test limit is 4 v.

The maximum test value is exceeded at the worst case by 3.78 v with a total change from nominal of 4.67 v. This indicates that tight restrictions must be placed on the input parameter variations. The output must be restricted to 19 percent of its present worst-case variation. The PERCENT CHANGE column states that input parameters 16, 12, and 4 contribute 94.4 percent of the change. If these input parameters are restricted to very little variation (approximately 10 percent), the worst-case maximum should not exceed the test value. This is an extreme restriction and the possibility of shifting the mean value to allow a greater variation should be considered.

The minimum test value is exceeded by 2.23 v with a variation of 3.34 v from nominal. The output variation from nominal must be restricted by 67 percent of its present variation. Input parameters 12, 13, 4, and 16 contribute 93.8 percent. If they are restricted to 71 percent of their present variation, the worst-case minimum will not be exceeded. It should be noted that input parameters 16, 12, and 4 are being restricted 71 percent of their present variation in one direction and 90 percent in the other direction. These restrictions are too tight and indicate that either a circuit redesign is necessary or the test limits must be widened.

D. SUMMARY OF MANDEX WORST-CASE ANALYSIS FOR SAMPLE CIRCUIT

The initial consideration in deciding what changes should be made in the circuit are the failures that cannot be corrected by changing components. The most obvious of these are the equivalent circuit failures. The summary sheet in the computer analysis indicates that there was an equivalent circuit failure; i.e., the transistor saturated or cut off in 28 of the 39 tests. As was pointed out in the discussion on output parameter 16, these failures cannot be eliminated by changing circuit components. If a lower input voltage, resulting in a lower output voltage, is not acceptable, a circuit redesign is in order. The second noncorrectable failure was the phase shift. Again, either the limits must be widened or the circuit redesigned. It should be noted that a decrease in input voltage will not affect the phase shift because e_{in} has a partial of zero with respect to the phase shift.

Consideration of the corrections of the other failures would be postponed until the circuit was redesigned or a new computer-run with a lower e_{in} was received.

APPENDIX C

RELIABILITY/DESIGN ANALYSIS CHECKLIST

The succeeding sections are checklists to aid the reliability design analysis team in the day-by-day review and monitoring of Apollo designs. Included in early paragraphs are factors which should be checked for all types of drawings. Other sections list check points applicable to specific types of designs. The use of appropriate checklists will reduce the amount of time required during formal review and reduce the number of drawing changes, otherwise necessary, because of design deficiencies.

The following checklist is provided as an aid to the designer in auditing his design. While this list may duplicate some of the items on the checklist used by the Apollo Reliability engineer in day-by-day review, the basic purpose of this list is self-discipline of the designer in the development of his designs.

BASIC SYSTEM CONSIDERATIONS

1. Can the system be simplified?
   a. Have established system designs been used wherever practical?
   b. Have trade-off considerations been reviewed? Has a study been made with formal computations to determine trade-offs? Have alternate designs been considered?

2. Does the design include the "man-in-the-loop" concept to support the reliability and crew safety requirements?

3. Is redundancy necessary to meet the reliability requirements? Has redundancy been optimized?

4. Have reliability and crew safety estimates been made?
   a. Do the estimates equal or exceed the reliability requirements apportioned to this system, subsystem, component, or part?

5. Have sequentially propagating failures been eliminated to the greatest extent possible?
   a. Are questionable or weak areas evident? Can they be improved or eliminated within the scope of this design?
   b. Is the system designed to be fail safe? Have the effects of failure been minimized?

6. Is the system compatible with all functional and environmental parameters, i.e. acceleration, shock, temperature, etc.?
   a. Can design degradation resulting from critical environments be reduced by further design development; creation of an alternate environment, i.e. cooling, shock mounting, encapsulating, etc.?

7. Will the design accommodate all variations of loading factors which may affect operation or reliability, such as those of voltage, pressure, current, flow rate, and electrical or mechanical loads?
   a. Are all components adequately derated for system stress parameters, such as pressure, flow rates, voltage, current, and power?
   b. Are all components adequately derated for environmental conditions, such as temperature, vibration, altitude, acceleration, and shock?

8. Are there adequate provisions to protect specific components from radiation, hard vacuum, micrometeorite impact, etc.?

9. Are there any potential installation stresses?
   a. Are there adequate provisions to eliminate combined, self-induced installation and environmental stresses?
   b. Does sterilization processing introduce residual stresses, compatibility problems, or other reliability degrading influences?*

10. Has documentation been accomplished?
    a. Have the effects of speed, stability, maneuverability and expected environments been evaluated and compiled into a formal report?
    b. Has a system of interconnecting grounds been established and documented?
    c. Has a report been prepared using value engineering techniques to determine the relative actual value of each function specified and to balance the effect of each function with regard to reliability, functional capabilities, environments, weight, volume, maintainability, and cost?
    d. Have system evaluation test studies, trade-off considerations, and unique functional and environmental requirements been documented in a formal report and submitted to responsible design units?

PART SELECTION

1. Has adequate consideration been given to selection of component parts?

2. Has reliability analysis been completed and a report prepared showing the estimated reliability of functional modules?

*Heating or other sterilization processes to prevent the spacecraft and its equipment from contaminating the moon.

3. Are qualified units of all specified components available? If not, are adequate qualification and reliability tests programmed?

4. Has use of components or parts which require hand selection been avoided to the greatest extent possible?

5. Will the selected qualified parts be used within the conditions for which they have been qualified?

EQUIPMENT DESIGN

1. Has a system schematic for this equipment been prepared and subjected to a reliability review?

2. Will producibility problems be encountered? Will reliability be degraded by production processes and techniques required?

3. Will assembly methods (e.g., welding, soldering, brazing, crimping, swaging) damage component parts?

4. Are special precautions and/or techniques called out unnecessarily?

5. Is incorrect assembly possible?

6. Are all tolerances sufficiently small? Are any tolerances unnecessarily small?

7. Are operating and maintenance personnel protected against electric shock, excessive temperature, and mechanical hazards?

8. Are interference and running fits properly specified?

9. Has adequate creepage distance and air gap been provided for the design voltage?

10. Are materials and equipment suitable for the application?
    a. Does the equipment employ lacquers, varnishes, silicons, plastics, or solvents that may evaporate or boil off and leave inadequate insulation?
    b. Does any of the insulation material contain salts or any other substance that will dissolve in water and thus provide leakage paths for electrolytic action?
    c. Are all insulating materials nonhygroscopic in nature?

11. Are over-voltage and under-voltage characteristics satisfactory for the usage intended?
    a. Are starting current transient characteristics compatible with the electrical system and the individual system involved?

12. Is the equipment packaged correctly? Are the chassis adequately sealed to insure against internal corrosion?

13. Does the location of component parts provide a minimum of interconnecting joints?

14. Have sources of stress concentration been eliminated by design, material selection, and/or material treatment in such areas as sharp corners and insufficient fillet radii; short bend radii; eccentric load paths; abrupt section change; steel stamped numbering on areas of high stress; excessively rough surface finish; nonmetallic inclusions, pipe seams, ingot patterns, segregation, etc., in raw materials?
    a. Have thermal stresses and differential thermal expansion been considered?

15. Do stops allow for deflection and wear during service life?
    a. Are stops which can take full operating force provided to prevent over-travel?

16. Have retaining, locking, or snap rings been eliminated where possible?

17. Are fastener hole sizes and tolerances compatible with part functions?

18. Will the equipment be exposed to explosive gases or vapors? If so, is it explosion proof?
    a. Are construction materials subject to outgassing or liberating toxic products?

19. Is it adequately sealed against the entrance of foreign objects?

20. Has adequate care been exercised to prevent dissimilar metals from intimate contact?

21. Does the design require specific mounting attitude which could be eliminated by redesign?

MAINTENANCE

1. Is the equipment maintainable? Have maintenance problems been considered?
    a. Has a maintainability review been conducted and documented?

2. Are all components located for efficient trouble isolation and maintenance?

3. Has a preventative maintenance program been established which replaces components in advance of predicted failure?

4. Are servicing and adjustment points compatible with access to the installed unit?

5. Can failures be readily detected and isolated?
   a. Are test points provided to enable trouble shooting prior to equipment removal? Are test points subject to inducing failures, intermittents, etc.?
   b. Is the system sufficiently tolerant of variations in component part characteristics to permit replacement by off-the-shelf components?
   c. Are limited-life parts readily replaceable? Have limited-life parts been kept to a minimum? Is there adequate justification for use of the limited-life parts specified?
   d. Are components prone to undue deterioration during storage or use conditions?

6. Is proper lubrication specified?

7. Are special test equipment or tools required for adjustment, inspection, service, or overhaul? If so, are they justifiable?

   a. Is equipment subject to damage during servicing of adjacent equipment?
   b. Are internal controls, such as switches and adjustment screws, located close to dangerous voltages? If blind screwdriver adjustment must be made, are safety guides provided?

EQUIPMENT INSTALLATION

1. Is the installation prone to degrade system reliability?
   a. Have all aspects of the schematic and equipment installation drawings been evaluated to reveal possible degrading factors?

2. Do interconnecting wires, tubes, cables, push rods, or similar interconnections prevent or degrade access to system components?
   a. Does the location of components provide a minimum of interconnecting joints?
   b. Are riveted joints used as electrical conductors?
   c. Are interconnections protected against damage by maintenance and operating personnel?

3. Are all necessary torque values specified?

4. Is adequate wrench clearance and access provided for all bolts, screws, couplings, nuts, etc.? Can inspection positively distinguish a correct installation with the access provided?

5. Are all attachments properly secured by acceptable positive locking devices?

6. Are appropriate process specifications and all other necessary installation instructions called out?

7. Is equipment properly mounted for vibration and shock isolation? Are isolation mounts restricted by attach cables or hoses, and is adequate clearance provided from structure and other equipment?

8. Is the equipment properly cooled or ventilated to dissipate internal heat and to prevent excessive heating from adjacent equipment? Are adequate heat sinks provided in passive elements?

9. Can scrap or waste materials readily be detected and removed?

10. Are adequate provisions made to prevent entrapment of moisture or other fluids?

11. Is adequate allowance made for structural flexure?

12. Do cables, tubing, etc., exert torque on mating elements?

13. Do self-engaging devices (rack and panel disconnects) have adequate float? Are they accurately located? Is the guide engagement sufficiently ahead of the body engagement? Is the supporting structure rigid? Is the track tolerance compatible with the guide taper? Is track friction low?

ELECTRICAL AND ELECTRONIC DESIGNS

Part Parameters

1. Is there adequate application suitability and reliability data available to justify selection of parts?

2. Are part characteristics and requirements adequately specified in procurement documents and standards?

3. Have Minuteman-type parts been used only where applicable?

4. Has a parts improvement program been designed and initiated for all parts whose reliability is inadequate and yet for which no acceptable substitute parts can be found?

Capacitors

1. Is derating adequate for temperature and humidity variations?

2. Are capacitor containers designed for the changing pressure levels which will be encountered, so that changing pressure will not result in changing capacitance?

3. Are all paper capacitors hermetically sealed?

4. Are all ceramic capacitors in a-c or pulsating d-c circuits operated below the corona-starting voltage?

5. Are capacitors operating within the allowable voltages as derated for ambient conditions?
   a. If capacitors operate within their full tolerance range, will performance of the circuit be adversely influenced?
   b. Are electrolytic capacitors derated to the point where reforming may be required?

6. Has adequate allowance been made in capacitors for the change in dielectric constant with age, temperature, voltage, frequency, ferroelectric effects, piezoelectric effects, humidity?

Connectors

1. Are the highest reliability connectors available used in this design?
   a. Have connectors specified been selected from the Minuteman standard parts list?
   b. Are sealing provisions adequate?

2. Is the type of connector specified suitable for the application?

3. Are the connectors selected with solder cups of adequate size to accommodate the largest anticipated wire size?

4. Are adjacent connectors physically different or polarized so that mating connections cannot be reversed? (Color coding is inadequate.)

Diodes

1. Are the highest reliable diodes available used in this design?
   a. Have diodes specified been selected from the Minuteman standard parts list?
   b. Have you checked Military Standard 701B for recommended preferred lists of diodes?

2. Can diode lists be reduced by slight circuit changes to use one category instead of two? If the part is a new state-of-the-art device, have qualification tests been conducted, have production problems been completely solved, and is a second source available?

3. Has the power rating been derated to aid reliable operation?

4. Has degradation of initial parameter limits been accommodated in the circuit design?

5. Are ambient temperatures controlled, or heat sinks provided, to prevent "hot spots" which might create excessive junction temperatures within the diode.
   a. Are junction temperatures under all environments and operating conditions compatible with allocated failure budgets?

Electron Tubes

1. Has every effort been made to use a solid-state device rather than a tube?

2. Are special high reliability tubes specified to the greatest extent possible?

3. Will any tube be subjected to all maximum ratings simultaneously?

4. Have precautions been taken to minimize surge currents?

5. Are all tubes mounted such that they are not normal to the direction of vibration?

6. Have precautions been taken to insure that rated filament voltage will not be exceeded?
   a. Is derating adequate for the maximum temperature expected?

Motors

1. Is rotational speed held to a minimum compatible with functional and reliability requirements?

2. Is the type of bearings and bearing lubricant adequate for the intended environment and rotational speed?

3. Is power derating compatible with functional and life requirements?

4. Is insulation adequate for the anticipated environment?

5. Are mounting provisions adequate to preclude transmission of heat, vibration, etc., to adjacent equipment?

Potentiometers

1. Is there adequate justification for using potentiometers?

2. Is the minimum life compatible with functional and reliability requirements?

3. Is the design such that effects of anticipated environments are minimized?

Relays

1. Is there sufficient justification for using relays?

2. Is the type of relay employed suitable for the application?

3. Are the relay coils protected against damaging transients?

4. Are relay contacts protected against arcing?
   a. Are all contacts on the relay utilized? (Paralleling contacts will increase reliability, provided that such paralleling is not done to increase the current rating, since different contacts of the same relay do not make and break simultaneously.)

5. Are all relays mounted such that the direction of motion of the armature is not coincident with the expected direction of shock?

Resistors

1. Are the highest reliability resistors available specified in this design?
   a. Have the resistors specified been selected from the Minuteman standard-parts list?

2. Has consideration been given to the size of the wire or wirewound resistors?

3. Have precautions been taken not to exceed the maximum rated voltage?

Switches

1. Have precautions been taken on motor-driven or similar actuated switches to prevent damaging over-travel?

2. Has adequate protection against arcing of contacts been provided?

Transformers

1. Is the transformer designed for the frequency at which it will operate? (Operation at frequencies above or below transformer design will cause higher than nominal temperature rise and shorter life.)

2. Have precautions been taken to limit voltage below the corona starting voltage?

Transistors

1. Are the highest reliable transistors used in this design?

2. Have transistors specified been selected from the Minuteman standard-parts lists?

3. If the desired part is not available in the Minuteman-standard parts list, have you checked Military Standard 701B for recommended preferred lists of transistors?

4. Can transistor lists be reduced by slight circuit changes to use one category instead of two? If the part is a new state-of-the-art device, have qualification tests been completed, have production problems been completely solved, and is a second source available?

5. Has the power rating been derated to aid reliable operation?

6. Has degradation of initial parameter limits been accommodated in the circuit design?

7. Have voltage ratings been reduced to permit spikes?

8. Are ambient temperatures controlled or heat sinks provided to prevent "hot spots" which might create excessive junction temperatures within the transistor?

Wiring Installation

1. Do interconnecting wires prevent or degrade access to system components?

2. Are adequate provisions made to prevent entrapment of moisture or other fluids?

3. Are all wire harnesses properly routed and supported to prevent chafing? Will they remain chafe-free after normal use and servicing of the vehicle? Are chafing guards used where necessary? Are high temperature damping devices employed where necessary?

4. Can hydraulic or other fluids drip on exposed electrical terminals or wiring.

5. Is provision made to prevent twisting of wires during engagement of coupling devices?

6. Has adequate provision been made for removing insulating films and coatings at all grounding points?

7. Does the design minimize the tendency toward cold solder joints? Can flux be readily removed?

8. Are the proper joining processes and materials employed? Have blind joints been eliminated? Can joined surfaces be 100 percent inspected?
   a. Are riveted joints used as electrical conductors?

9. Is single-point grounding employed?

10. Have wire coding and proper wire sizes been specified?

11. In difficult installations are premolded harnesses employed?

12. Are radio-shielded wiring and harnesses employed where required?

13. Has point-to-point wiring been minimized?

14. Is it physically possible to cross-connect wiring between adjacent fittings of the same type?

15. Are wires properly routed to reduce electrostatic and electromagnetic coupling?

16. Are component terminals improperly used as terminal strips? Are terminals adequate for the current and voltage involved? Are terminals shielded against short circuits? Are terminals marked and covered properly where high voltage is involved? Are terminals properly identified?

FLUID SYSTEMS DESIGN

Basic System Considerations

1. Has a complete dynamic analysis of the system, including environmental influence, been made?

2. Has adequate surge damping been provided at all critical points in the system to reduce both catastrophic surges and lesser fatiguing surges, e.g., from fast-acting cylinders, accumulators, pump pulses, valve opening and closing?

3. Have any dead-end lines (pressure switches, gauges) been located near the pump outlet?

4. Is it possible for any accumulator to dump into the reservoir or pump housing?

5. Are lines and components (particularly swivels and hoses) relieved from system pressure during nonoperating flight periods?

6. Are shuttle valves (hydraulic-pneumatic) mounted directly on the actuating cylinders?

7. Are hydraulic pump case drain lines separated to prevent cross contamination?

8. Does each drain line include filters, and are filters sized to accommodate the function and installed to preclude bypass?

9. Has the maximum contamination level been determined and documented?

10. Are there adequate provisions for particle size, count, and distribution determinations?

11. Is there adequate protection from contamination by GSE and through proper venting?

12. Are fill and drain provisions adequate and readily accessible?

13. Are servicing lines difficult to handle? Do they induce stress in mating parts?

14. Are all materials of construction compatible with the fluids used and with the contamination requirements?

15. Will vent system capacity preclude damage under system pressure?

16. Will fluid spillage from the vent system contaminate adjacent areas or cause fire or other hazards during ground operations or in flight?

Equipment Design

1. Are snap rings used to retain parts against hydraulic or mechanical loads?

2. Are adjustments held by self-locking nuts, rather than jam nuts or safety wire?

3. Is the design restricted to a particular mounting attitude?

4. Does pressure unbalance exist for either system or return pressure?

5. Have split coil solenoids been avoided?

6. Is the unit unnecessarily sensitive to contamination so that erratic or unpredictable operation may result? (Ref. pilot operated valves, etc.)

7. Are pressure traps built in so that leakage past seals causes overloading of end caps?

8. Will mounting cause the case to warp and result in binding of moving parts?

9. Are parts likely to be jammed or broken due to overtravel or misrigging?

10. Does drawing specify the minimum radii permissible between adjacent surfaces, and that all sharp edges must be broken?

11. Is the part design compatible with plating process specified, e.g., no plating required on small internal radii, etc.?

12. Have wet solenoid coils been avoided?

13. Is component likely to deflect to an out-of-tolerance condition when under pressure or when tightened during assembly?

14. Are small tapers specified which will make disassembly difficult and which will cause large stress concentration?

15. Are locating pins positioned so that possible overdrilling of holes will weaken or scrap the part?

16. Are adequate, positive retention devices used on pressed-in parts, such as filters?

17. Is welding permitted without normalizing?

18. Can fittings, screws, or other threaded parts be screwed in excessively to cause interference?

19. Are pipe plugs and tapered pipe threads prohibited?

20. Are close-running fits used between parts with different coefficients of expansion so that binding will occur when exposed to temperature extremes?

21. Are castings used as load-carrying members?

22. Is either soft solder or cadmium plating used internally?

23. Have the effects of intergranular or stress corrosion in processing as well as application been considered? Can other alloys less susceptible to this condition be substituted?

24. Is machining concentricity dependent on location from threads?

25. Will springs cause parts to cock and bind?

26. Are springs designed so that they are likely to yield or take an undesirable permanent set?

27. Will internal adjustments affect external operation, e.g., will valve adjustment affect handle position?

28. Can the part be installed incorrectly?

29. Will sudden release of operating force damage the part?

30. Is flow path free from turbulent restriction?

31. Are pressure-sensitive devices rugged enough to withstand maximum surges?

32. Can part be damaged by back or return pressure surges?

33. Are the seal installations properly designed?
    a. Can the number of dynamic or static seals be reduced?
    b. Are face seals used between adjoining members that breathe or flex under mechanical or hydraulic loads causing leakage?
    c. Is installation likely to damage seals during assembly, e.g., sharp corners or parts over which unsupported seal must pass?
    d. Is O-ring under tension?
    e. Does installation require nonstandard O-ring cross section?
    f. Have nonreplaceable seals been avoided?
    g. Has adequate squeeze been specified?
    h. Are rod seals adequately lubricated to prevent spiral failures after long periods of nonuse?
    i. Is O-ring properly contained to prohibit stretching?
    j. Can O-ring be "washed out" under conditions of high flow rates?

Equipment Installation

1. Are wearout items, such as seals, readily identified and available for inspection and replacement?

2. Can filter elements be replaced without removing other equipment and without damage to other equipment due to oil spillage?

3. Are fuses provided for all pressure-sensing devices?

4. Can the reservoir be easily serviced and checked?

Tubing Installation

1. Is tubing adequately supported and routed to prevent chafing?

2. Are flex lines and swivel provided with adequate clearance?

3. Can both ends of each tube be inspected for proper length and alignment prior to engaging coupling nuts?

4. Is it necessary to bend tubing during installation?

5. Can lines be more directly routed with fewer joints required?

6. Is adequate clearance provided for each coupling for proper installation, wrench use, and inspection?

7. Can tubing flex in its installation without chafing?

8. Is line likely to be damaged during torquing of its fittings or adjacent fittings? Are provisions for two wrench flats included where torsion is possible during installation?

9. Can swivel fittings and flex lines be replaced with torque tubes?

10. Has brazing or welding been given due consideration to reduce potential joint leakage?

11. Are the number of flexible lines minimized? Can swivel or expansion joints be employed in place of flexible sections?

12. Are there adequate provisions for leak checks in the systems after installation?

13. Are preformed rigid and flexible lines used where installation is tight?

14. Can tubing joints be combined in a common manifold?

Mechanical Systems Design

1. Can bellcranks or levers be installed incorrectly so as to change the mechanical advantage?

2. Are provisions made for a straightforward rigging procedure?

3. Are interference and running fits properly specified?

CREW PROVISION CONSIDERATIONS

Has a human factors review been conducted and documented to assure man-machine compatibility?

Instruments and Display Systems

1. Is the instrument grouping such that scanning may be performed with a minimum of eye movement?

2. Is instrument configuration and location such that parallax is minimized?

3. Can the instrument be read to accuracy required by the operator?

4. Is the display system free of features which might produce ambiguity or invite gross reading errors?

5. Are changes in readings easily detected?

6. Are multiple monitoring instruments arranged so that normal positions are in line, and an abnormal condition is readily detected?

7. Can indicators be observed even when field of view is limited by clothing, visors, etc.?

8. Is mental translation from one unit to another avoided?

9. Are unsafe ranges of operation clearly shown on indicators?

10. Is the relationship of the required control movements natural to the expected instrument movement?

11. Are the instruments readily distinguishable from each other?

12. Will the operator be aware of an inoperative condition?

13. Is illumination satisfactory under all conditions of expected operation?

14. Is adequate protection provided against glare and shafting?

15. Is general illumination adequate for retention of depth perception?

Consoles and Controls

1. Are all controls provided with detents or other positive position "feel" to prevent inadvertent partial operation?

2. Are control handles designed to prevent inadvertent motion, complete or partial, toward one position during operation toward another?

3. Are distinctive shapes provided for control knobs or handles, switches, levers, etc., where they must be operated by "feel"?

4. Are controls clearly identified and appropriate position markings shown?

5. Are knobs and handle sizes consistent with operating force?

6. Are all controls within reach of operator when he is restrained for any reason?

7. Are all adjustment handles, knobs, or levers positively secured against creep throughout entire operating range and against all feedback forces vibrations from connected equipment?

8. Are location, size, and shape suitable for operation with applicable garments?

9. Are control position indications located so that they are not obscured by the hand when operating controls?

ESCAPE SURVIVAL AND EARTH-LANDING SYSTEMS

1. Is the operation simple and straightforward?

2. Can the system be actuated under accelerations which might be expected during uncontrolled flight?

3. Is sequencing of preparatory or secondary operations critical to operator's survival?

4. Has maximum effort been made to avoid the need for retraction of protuberances from the escape path? If retraction requirements are unavoidable, are such items provided with interlocks and manual overrides to assure that the escape mechanism is not activated until retraction is effected? Has the interlock system been kept simple?

5. Are alternate means of escape provided if the primary system should fail?

6. Can crewmen disengage from the system quickly with necessary emergency equipment?

7. Are precautions taken to insure against inadvertent initiation of emergency sequences, or operation of emergency equipment, during launch operations or flight?

8. Are adequate safety devices correctly employed in the design?

9. Is the design such that pyrotechnic lines, cables, etc., cannot be inadvertently switched during maintenance?

10. Is the equipment safe to ground personnel?

11. Are fragile items, e.g., parachute, impact bags, etc., protected against damage or deterioration from weather and maintenance personnel?

12. Are checkout provisions made for all critical functions?

13. Have all elements of escape, survival, and earthlanding techniques and equipment been subjected to reliability review and analysis?

SPECIFICATION CONTROL DRAWINGS AND DOCUMENTATION

1. Are all performance parameters clearly defined and acceptable tolerances given?

2. Is reliability stated as a quantitative design requirements? Are reliability requirements translated into proper design parameters?

3. Are the expected reliability implementation requirements defined?
   a. Are applicable specifications and documents defined?
   b. Is stress analysis defined?
   c. Are reliability estimates defined?
   d. Are failure mode and effect analyses defined?
   e. Are design reviews defined?
   f. Are reliability and quality assurance organizations and responsibilities defined?

4. Is a test program established to demonstrate the reliability and crew safety attainment of equipment?
   a. Will equipment be entirely suitable for the intended environments?
   b. Will equipment repeatedly meet the necessary performance requirements?
   c. Will equipment provide reliable performance with low maintenance requirements for an acceptable service life?
   d. Will equipment assure applicability and continuity of data through all levels of assembly?
   e. Is equipment completely compatible with the design and objectives of the over-all test program and does it lend itself to statistical treatment of results?

5. Are all reports defined so that adequate knowledge of the test results will be conveyed?
   a. Are development tests defined?
   b. Are qualification tests defined?

c. Are acceptance tests defined?
d. Are failure reports defined?
e. Are failure analysis and corrective action defined?
f. Is previous history of this or similar designs defined?

6. Are all report dates firmly stated to assure information receipt in a timely manner?

7. Are requirements delineated to assure control measures and permission to review facilities and tests?

8. Is a failure defined to preclude various interpretations of test results?

9. Has the anticipated environment been completely defined?

10. Has supplier responsibility for all requirements been clearly defined?

11. Are all critical physical characteristics clearly defined and are acceptable tolerances given?

12. Is appropriate derating of all parts specified?

13. Are conditions for acceptance clearly defined?

14. Are the requirements so stated that proprietary interests cannot be construed to preclude availability of all data necessary to conduct an independent review?

15. Are design review data requirements clearly defined?

APPENDIX D

APOLLO PROGRAM DESIGN REVIEW PROCEDURE

The purpose of this appendix is to establish formal procedures and responsibilities for the implementation and accomplishment of Apollo program design reviews in accordance with Section IV of this document.

DESIGN REVIEW SCHEDULES

Design review specialists located in the Design Review Group and working under the direction of the Design Review Board chairman will be responsible for the preparation of schedules in coordination with the responsible engineering groups. The schedule will be based upon current Engineering planning and availability of material for the particular design review required and will reflect Engineering concurrence.

DESIGN REVIEW MATERIAL

Responsible departments will assist the Design Review Group in preparing the package requirements for a particular review as identified in Section IV of this document. Additional copies of all unreleased or not readily available material will be arranged for by the Design Review Group. The material must be available prior to the scheduled meetings as follows:

Preliminary design reviews	10 days
Major design reviews	17 days
Application design reviews	21 days
Special design reviews	as appropriate

The Design Review Group will distribute the material to the board members, indicated in Section IV, not less than the following working days prior to the scheduled meeting:

Preliminary design review	5 days
Major design review	10 days
Application design review	12 days
Special design reviews	as appropriate

Material which is readily available through normal channels will be referenced in the Notice of Meeting. It will be the responsibility of each particular member to obtain copies for his own use.

DESIGN REVIEW EVALUATION

Design Review Board members will conduct an intensive review of all material submitted with and referenced on the Notice of Meeting form. Primary attention shall be given to those areas which are the direct responsibility of the group performing the review. Specific vigilance should be given to sections of the design which can be potential problem areas. Design Review Board members will submit their findings (proposed agenda items) to the Design Review Group by internal letter at least one working day prior to meeting date for Preliminary Review, two working days prior to meeting date for major reviews, and three working days prior to meeting date for application reviews. The proposed agenda items should be sufficiently clear and descriptive to allow intelligent discussion with the involved design group by the design review specialist.

All proposed agenda items, including those generated within the Design Review Group, will be discussed with the responsible group representative to resolve all possible minor items prior to the scheduled meeting. Remaining items requiring Board consideration will be placed on the firm agenda for the scheduled design review.

DESIGN REVIEW BOARD MEETING

Design Review Board meetings will be held when firm agenda items remain after the Design Review Board evaluation has been completed. The firm agenda items are discussed at the meeting to determine if, in the opinion of the Board, additional effort or possible design changes should be considered to correct an identified problem area. (Note: It is not the purpose of the Design Review Board meeting to propose a specific design change or to undertake actual corrective action.) The design being reviewed will receive board disposition as indicated in Section IV of this document.

DESIGN REVIEW REPORT

The design review specialist will prepare a report of the board-recommended action for distribution to all board members. Action items from the report will be resolved to the satisfaction of the designated responsible board member and the Chief Engineer. An internal letter will be sent to the Design Review Board and Group, indicating the method of resolution, for board approval and group record. In all instances final authority rests with the program Chief Engineer.

APPENDIX E

CONTRACTUAL RELIABILITY DOCUMENTATION AND REPORTS

RELIABILITY DIRECT DOCUMENTATION

In accordance with Exhibit I, of the Definitive Contract (NAS9-150) the following are NASA required documents submitted by Apollo Reliability.

Reliability Program Plan (SID 62-203)

This is the basic document which describes the overall plan for the conduct of the Project Apollo reliability effort. The plan describes and schedules all phases of the reliability effort. It was submitted to NASA 30 days after contract go-ahead and is reviewed and revised as necessary.

Quarterly Reliability Status Report (SID 62-557)

This report provides a comprehensive view of the reliability program, including the current demonstrated reliability level for each major element and component, problems, failure analyses, results of corrective action taken or corrective action proposed, test status, and progress anticipated in the next report period.

Apollo General Test Plan and Procedures (SID 62-109)

This document includes the complete Apollo test program from development through flight testing of complete spacecraft. Volume I, SID 62-109-1, defines the test logic and emphasizes test integration, continuity of data through all test phases, and the reliability assessment plan. Volume 2, SID 62-109-2, details the development testing of individual systems. Volume 3, SID 62-109-3, replaces the Qualification-Reliability Test Plan, SID 62-204, and encompasses the complete ground qualification program for subsystems, GSE, and applicable lower levels of assembly. Volume 4, SID 62-109-4, delineates the specific acceptance test procedures to be employed at each applicable level of assembly. Volume 5, SID 62-109-5, defines all multiple (combined) systems tests on ground spacecraft and boilerplate or spacecraft flights. The test plan is supplemented by detailed test procedures and standards for data reporting, corrective action, and equipment performance analysis. Such procedures govern both S&ID and supplier tests. Special statistically

designed experiments and sampling plans are delineated in this document. Reoriented test plans are to be submitted to NASA periodically; individual test procedures are to be submitted to NASA upon request.

Nonconformance Report

A failure report, Nonconformance Report (NCR) Form 963-M, is prepared on all failures which occur on contractor-furnished and government-furnished equipment during all phases of assembly, testing, operation, etc. Details of the failure reporting and analysis system are found in Section VIII.

Monthly Failure Summary (SID 62-822)

This report is submitted to NASA and summarizes the failure reports. It also presents a diagnostic analysis of all failures with corrective action taken or proposed. Additional summaries of and status on significant failure or problem areas are contained in the quarterly reliability status report.

Qualification Status List (SID 62-784)

The qualification status list shows the status of the planned and completed qualification of each part, component, and subsystem, as well as those items for which valid data exist, thus not requiring further qualification. (See Section VII, Qualification Tests.) Revisions are made as required.

RELIABILITY SUPPORT DOCUMENTATION

The Apollo Reliability Manager is responsible for the preparation and submittal of portions of reports which originate outside the reliability organization. These reports include the Monthly Progress Report, Final Report, Test Plan, and Hardware List.

APPENDIX F

RELIABILITY SUPPLIER SURVEYS

It is the policy of S&ID to select suppliers on the basis of their capabilities to produce and supply hardware in accordance with established program reliability standards. The final selection of a supplier is determined after a comprehensive evaluation of his capabilities.

To assure consistent reliability evaluation between suppliers, a handbook has been prepared which provides the Reliability Engineering participant with general guidance in evaluating supplier's systems for controlling product integrity in conformance with government or NAA specifications and quality assurance provisions. Types of surveys which are performed by Reliability Engineering are:

1. Initial Reliability Engineering Survey. An initial or pre-award survey is conducted when available information, within the NAA corporate structure, regarding a supplier's reliability program and/or a major subcontract assurance of product reliability is inadequate or inconclusive. The initial survey may be conducted independently by Reliability Engineering or by team effort with Purchasing and representatives from Quality Control and other concerned S&ID departments.

2. Follow-Up. The follow-up is a resurvey of a supplier to verify that deficiencies reported in the initial survey have been corrected, or to verify continued conformance with documented requirements. When practical, the reliability representative who conducted the initial survey will be assigned.

3. Periodic Resurvey. Periodic resurveys are conducted when changes which may affect a supplier's reliability program occur, such as reorganization, relocation or expansion, and major additions or deletions of equipment. Resurveys are also conducted when the reliability of incoming material has deteriorated, requiring prompt corrective action by a supplier, and when considerable time has elapsed since the initial survey was conducted.

The handbook used for the initial (pre-award) survey defines the method of preparing for and conducting the surveys and provides a definitive check list (included herein) to enable the survey representative to systematically record the supplier's rating. Figure F-1 shows the Reliability Information Requirements form.

Firm Name: _____ Telephone No. _____

Address: _____ City: _____ State: _____

N.A.A. Product Concerned: _____

Project: _____ System: _____

Date of Last Survey: _____ Survey Type: ____ Survey Date: _____

Personnel Contacted:

Name: _____ Title: _____

_____ _____

_____ _____

_____ _____

_____ _____

Reliability Organization Reports to: Engr. ☐ Q.C. ☐ Other _____
Personnel:

Total Employed: _____ Director: Avg. Yrs. Experience _____ Degrees _____

Design Engr.: _____ Manager: _____ _____

Manufacturing: _____ Supervisor _____ _____

Number

Failure Reporting System: Yes ☐ No ☐ Engineers: Reliability _____

Reliability Management
Reports to Whom: _____

Date reporting system: Type equipment used (IBM Yes ☐ No ☐ Computer Yes ☐ No ☐
Environmental & Test Lab used outside of company: _____

_____

_____

_____

Scoring: % Acceptability

I.	Management and Organization	_____
II.	Planning	_____
III.	Technical/Reliability Evaluation	_____
IV.	Test	_____
V.	Failure Report, Analysis and Corrective Action	_____
VI.	Training and Related Functions	_____
VII.	Documentation	_____
	TOTAL	_____

Surveyor _____ Acceptability Grade: _____

Figure F-1. Reliability Information Requirements

RELIABILITY ENGINEERING QUESTIONNAIRE BASED ON MIL-R-27542

Rating:	1	2	3	A	P

I. MANAGEMENT AND ORGANIZATION

A. Management

1. Does the supplier's management indicate a positive attitude toward reliability?

2. Do the supplier's management policies reflect an awareness of reliability?

3. Does the supplier's management have experience in reliability programs? (Obtain list of programs and applicable government specifications for inclusion in the supplementary report.)

4. Is the reliability management adequately staffed?

5. Is the supplier's management reliability policy reflected in its supplier relations?

	Rating:	1	2	3	A	P
B.	Organization					
1.	Does the supplier have a single group responsible for overall direction of reliability? If not, do the supplier's Design, Quality Control, and Manufacturing sections have reliability direction and assign responsibility and authority within the groups to implement the reliability program?					
2.	Do the supplier reliability groups report to top management levels?					
3.	Have adequate responsibilities and authority been given to persons responsible for implementing reliability policies?					
4.	Is the supplier's reliability group adequately staffed?					
5.	Are the personnel distributed in a manner that staffs the analysis, test, data handling, and statistics sub-groups sufficiently for efficient functioning of the reliability group?					

	Rating:	1	2	3	A	P
6.	Does the supplier's reliability group's direction enter into the Design, Quality Control, Manufacturing and Procurement areas?					

II. PLANNING

A. Program

1.	Does the supplier reliability program provide for the continual monitoring of the design, development, testing, and production efforts for assessment reporting of reliability?					
2.	Does the supplier specify the same reliability program requirements stated herein to his suppliers? (If a written procedure is not available, a description of how this is accomplished should be included in the supplementary report.)					
3.	Are the results or the assessments reviewed for possible updating of the program?					

	Rating:	1	2	3	A	P
B. Personnel						
1. Do the personnel assigned to reliability activities (analysis and testing) have adequate education, experience, and capabilities to adequately perform their work?						
2. Do the personnel assigned to support reliability (data handling, statistics, field support, etc.) have adequate education, experience and capabilities to perform their work?						
C. Facilities Support						
1. Does the supplier have in-plant test facilities capable and available to test the equipment to the required specifications?						
1.1 Required Specifications for test list.						
1.2 List equipment required in-house (Min.)	To be listed by surveyor					
1.3 List equipment usable in Govt. or Commercial labs.						

	Rating:	1	2	3	A	P
2.	Does the supplier have commercial or governmental test laboratories available to supplement his facilities? (Obtain list of laboratories the supplier intends to use in the event of a contract with N. A. A.)					
3.	Does the supplier have the proper facilities to perform and maintain the calibration and control of test equipment? (Obtain copy of suppliers applicable Quality Control procedures.)					
4.	Does the supplier have facilities for the laboratory analysis of malfunctions or failures?					
D.	Formal Procedure					
1.	Does the supplier define the following: Each task and study to be performed. Task assignment. Method of control for execution of tasks. Scheduled start and completion dates.					

	Rating:	1	2	3	A	P
2.	Does the supplier reliability program provide for the monitoring of the program status and results obtained? (If a written procedure is not available as requested in Section VII-3a, a description should be included in the supplementary report.)					
3.	Does the supplier have a system assuring the control of drawings, technical requirements, specifications, and all changes to these documents? (If a written procedure is available, a description of how this is accomplished should be included in the supplementary report.)					
	RESULTS					
	Rating:	1	2	3	A	P
III.	TECHNICAL/RELIABILITY EVALUATION					
A.	Inherent Reliability and Safety					
1.	Does the supplier establish reliability goals for each equipment item?					
2.	Does the supplier's reliability personnel conduct numerical, failure mode and stress analyses (where applicable) on all equipment items?					

Rating:	1	2	3	A	P
3. Has he performed the functions described in 1 and 2 on other programs? (Obtain sample reports as requested in Section VII-6, 7 and 8, and names of programs in which supplier participated.)					
B. Reliability Input-To-Design, Quality Control and Manufacturing					
1. Does the supplier have a program for part and component selection and evaluation that emphasizes reliability in addition to performance parameters?					
2. Is the list of selected parts and components transmitted to the designer along with generic failure rate data to assist designers?					
3. Does the supplier assign to the persons responsible for component selection and approval the authority to approve of all deviations from the list of approved items?					

	Rating:	1	2	3	A	P
4.	Does the supplier have a supplier rating program?					
5.	Does the reliability group review all test procedures on all parts and components?					
6.	Does the reliability group work with the design groups from the inception of the design to assure a reliable unit with minimum delay?					
7.	Does the reliability group review and insert reliability items into all procurement specifications?					

C. Design Review

1.	Does the supplier conduct equipment design review (with support from the reliability group) before designs are finalized?					

RESULTS _____

Rating:	1	2	3	A	P
IV. TEST					
A. Formal Test Plan and Procedure					
1. Does the supplier provide for the testing and evaluation of the packaging materials and techniques?					
2. Does the supplier provide for partial or complete requalification when design or production changes have been made which cannot be evaluated by acceptance tests?					
3. Has the supplier documented his inspection system and procedure? (Obtain copy of supplier's applicable Quality Control procedure.)					
B. Knowledge					
1. Do the supplier test engineers have experience or knowledge of the techniques involved in implementing an experimental design with factorial or factorial sequential tests?					

Rating:	1	2	3	A	P
2. Do the supplier test engineers have experience in directing the single and combined environmental tests?					
C. Data Feedback					
1. Does the supplier disseminate test data to: Engineering Quality Control Manufacturing Procurement for product improvement or for use in design review? (If written procedure is not available as requested in Section VII-6, a description should be included in the supplementary report.)					

RESULTS _____

Rating:	1	2	3	A	P

V. FAILURE FOLLOW-UP

A. Reporting

1. Does the supplier have an established system for collecting, analyzing and recording all significant data concerning failures and malfunctions occurring in-plant or at any other test or installation facility for which the supplier has primary responsibility? (If a written procedure is not available as requested in VII-5, a description should be included in the supplementary report.)

2. Has the supplier described his failure reporting system, including failure and malfunction reporting forms and flow charts?

3. Are these failure reports used as a basis for failure analysis?

	Rating:	1	2	3	A	P
4.	Has the supplier provided for failure and malfunction reporting during all phases of the program such as: Receiving In-Process testing Final check-out Development-Qualification Reliability testing Other					
5.	Does the supplier failure report include a complete documentation of the environmental and operating conditions to which the equipment has been subjected prior to and during the failure?					
B.	Analysis					
1.	Does the supplier failure reporting program include a laboratory diagnosis and analysis of failures and malfunctions? (Determine level of person conducting the diagnosis and analysis, and include in the supplementary report.)					
2.	Does the failure analysis categorize failures according to design inadequacy, workmanship error, testing error, secondary failure, or parts failure?					

Rating:	1	2	3	A	P
3. Does the supplier have a system of informing his customer, his Engineering Department and suppliers, of the tests and allow them to take part in the diagnosis and analysis?					
4. Does the supplier document all steps taken to determine the cause of failure, using photographs or sketches with specific measurements where applicable and parts dissected to whatever degree necessary to establish the ultimate cause of failure?					
5. Do the supplier's specialists in human factors review all failures described as human initiated failures?					

C. Corrective Action

1. Has the supplier an effective means for initiating and disposing of corrective action recommendations resulting from analysis of malfunction or problem reports?					

Rating:	1	2	3	A	P
2. Has the supplier established a procedure for identifying problem areas that require action and reporting these open reliability problems periodically until corrective action has been accomplished?					
RESULTS					

Rating:	1	2	3	A	P
VI. TRAINING AND RELATED FUNCTIONS					
A. Personnel Selection					
1. Is the supplier's personnel department aware of the need for reliability oriented or trained personnel?					
2. Does the supplier use discrimination in its selection of personnel to the extent of hiring people who have had experience in programs that have had high reliability requirements?					

Rating:	1	2	3	A	P
B. Personnel Training					
1. Does the supplier have a training program to assure that all employees (technicians, skilled craftsmen, engineers, etc.) keep pace with advancements in technology required to achieve optimum reliability?					
2. Does the supplier have a program for the dissemination of the latest information on reliability application and procedures or techniques which will enhance the reliability of the product?					
3. Does the supplier require the above of his suppliers?					
C. Motivation					
1. Does the supplier have a program to indoctrinate all of its employees and suppliers, whose work contributes to the product's reliability, in the need for reliability and their contribution to the products reliability?					

Rating:	1	2	3	A	P
2. Does the supplier have a procedure for assisting his suppliers in their reliability indoctrination of employees? (If a written procedure is not available, a description should be included in the supplementary report.)					

RESULTS _____

VII. DOCUMENTATION REQUIREMENTS (as sent to supplier.)

DOCUMENTATION REQUIREMENTS

Please attach copies of the following and submit to the Reliability Survey Engineer upon arrival.

1. Management policy implementing the reliability program.
2. Organization charts for Reliability and associated departments.
3. Documentation defining the responsibilities and authority of key personnel engaged in the reliability program.
4. Resumés, indicating education and experience of key personnel engaged in the reliability program.
5. Procedure for malfunction and problem report collecting, analyzing and recording, and method employed for follow-up to ensure corrective action is implemented where necessary.
6. Procedure for disseminating test, malfunction or procedure data throughout the company for product improvement or for use during design review.
7. Sample of historical data regarding failure rates and modes of failure for previously produced identical or similar equipment.

8. Sample reports of:

   Reliability Tests
   Failure Analysis
   Statistical Analysis
   Numerical Analysis (mathematical models, etc.)
   Prediction for engineering changes
   Establishment of reliability goals
   Trend Forecasting
   Reliability Assessments
   Stress Analysis
   Growth Curves
   Design Analysis

9. Sample of the malfunction and problem reporting form.

10. Complete reliability manual.

APPENDIX G

REFERENCE DOCUMENTS

NASA DOCUMENTS

NASA Publication on Quality Provisions for Space System Contractors National Aeronautics and Space Administration, NASA NPC 200-2 (4 April 1962).

Project Apollo, Comments on North American Aviation, Inc., Proposal RFP 9-150. Manned Spacecraft Center, Langley Air Force Base, Virginia (4 December 1961).

Project Apollo Command and Service Module Development Program, The Definitive Contract, NAS9-150, Confidential, NASA Manned Spacecraft Center, Houston 1, Texas (14 August 1963).

MILITARY SPECIFICATIONS

Reliability Program Requirements for Aerospace Systems, Subsystems, and Equipment. United States Air Force, MIL-R-27542 (28 June 1961), Amendment 1 (October 1961).

S&ID PROPOSALS, REPORTS, AND SPECIFICATIONS

Apollo General Test Plan, Volume I, General Test Plan Summary, Confidential. NAA S&ID, SID 62-109-1 (30 March 1963).

Apollo General Test Plan, Volume 3, Ground Qualification Test Plan, Confidential. NAA S&ID, SID 62-109-3 (30 March 1963).

Apollo General Test Plan, Volume 4, Acceptance Test Plan, Confidential. NAA S&ID, SID 62-109-4 (30 March 1963).

Apollo Qualification Status List. NAA S&ID, SID 62-784.

Apollo Quality Control Program Plan. NAA S&ID, SID 62-154.

Apollo Spacecraft Requirements. NAA S&ID, SID 62-700-2 (15 September 1962).

GSE, Performance and Interface Specification. NAA S&ID, SID 62-57 (15 May 1962).

General Specification, Human Engineering Design Criteria. NAA S&ID, MC 999-0007 (15 September 1962).

NASA Project Apollo Spacecraft Business Management Proposal, Vol. II, Parts 1, 2, and 3, Confidential. NAA S&ID, SID 61-281 (6 October 1961).

Reliability Parts Manual, Failure Rate and Application Data. NAA S&ID (November 1962).

Reliability Parts Manual, Preferred Parts. NAA S&ID (January 1963).

AUTONETICS REPORTS

Description and Comparison of Computer Methods of Circuit Analysis. NAA Autonetics Division, EM 6839 (30 June 1961).

Description of the Data Processing Problem for Minuteman High Reliability Electronic Parts. NAA Autonetics Division, EM 2493 (15 November 1961).

APPENDIX H

APPLICABLE DOCUMENT REQUIREMENTS AND DEVIATIONS

This appendix lists the existing S&ID documents that implement the requirements of specifications MIL-R-27542 (USAF) and NPC 200-2. Under the comments column heading are S&ID's objections and deviation requests. The paragraph numbers and statements in the requirements column are those of MIL-R-27542 (USAF) and NPC 200-2.

MIL-R-27542

REQUIREMENTS AND DEVIATIONS

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
3.0 REQUIREMENTS		
3.1 The reliability program shall recognize the concept of inherent reliability of design.	SID 62-203 Introduction	Test planning shall be predicated upon engineering rationale in lieu of statistical conclusions. Reliability demonstration shall not be a prerequisite for qualification.
Emphasis and effort shall include those activities necessary to assure retention of reliability during the manufacturing, development testing, and operational demonstration and use phases.	SID 62-203 Section I	
Where demonstration of reliability is specifically stated, such statements shall include an accompanying statement of the confidence level to which the reliability will be demonstrated.	SID 62-203 Section VII SID 62-109 SID 62-1405	
(a) Reliability must be a major factor in planning, management, and engineering.	SID 62-203 Section I	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
3.2 Submission of Data. Data as referenced or described herein by the paragraphs listed below shall be submitted by bidders or contractors at such times as required.	SID 62-203 Appendix E MC 999-0025 MC 999-0008 NAS9-150 Exhibit I	
3.3 Design Selection Phase. Proposals for systems, subsystems, and equipments submitted prior to the award of contract shall include an estimate of the maximum environmental and stress conditions to which the system may be subjected during its various life phases. The contractor shall develop an estimate of reliability which can be achieved during the development period covered by the contract and shall provide data which will validate this estimate. The contractor shall identify anticipated problem areas relative to the capability of parts, subsystems, and systems to withstand the estimated environmental or stress conditions and manufacturing limitations.	SID 62-109 Tables SID 62-203 Section II SID 62-203 Sections I and VIII	Proposal reference is not applicable. More accurate estimates of environmental and stress conditions have been submitted in Apollo Environmental Criteria for use in Subcontractors Specifications, SID 62-1388.

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
The manner of demonstration of the required reliability with confidence levels, where practicable, shall be specified.	SID 62-109 SID 62-1405	The manner of assessing the required reliability, where practical, shall be specified. Confidence in the amount and accuracy of the data collected shall be determined by the available data. Omit confidence level and replace "demonstration" with "assessment."
3.3.1 System Mode. The relationships between reliability and other system parameters shall be shown, e.g., reliability figures shall be included in the overall model of effectiveness for the system. All pertinent	SID 62-203 Section II	Relationships between reliability and crew safety are applicable.

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
success parameters (e.g., reaction, time, turn-around time, in-commission rate, effectiveness, availability, and launch rates) shall be included and, as applicable, each requirement shall be apportioned over the major elements and subsystems of the system.		References to weapon system parameters are not applicable.
3.3.3 Program Plan. The contractor shall include, as a separate section in his proposal for the system or subsystem, a description of the reliability program, including a detailed listing of specific tasks and the general procedures to implement and control these tasks.	SID 62-203	Proposal reference is not applicable. Exhibit I, NAS9-150 takes precedence.
These specific tasks shall include any parts improvement programs deemed necessary to meet reliability objectives.	SID 62-203 Section III	
The listing and reporting of accomplishment of these tasks shall be in a form that permits technical auditing by the procuring activity and the contractor for contractual compliance.	SID 62-203 Section V	
The reliability program plan shall provide the periodic reporting on the reliability activities specified hereinafter.	SID 62-203 Section V Appendix E	
The program description shall describe methods for determining, achieving, and demonstrating system reliability.	SID 62-203 General SID 62-109 SID 62-1405	Replace "demonstrating" with "assessing."

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
3.3.3.1 Reliability Organization. The program plan shall identify the organization responsible to management for the over-all reliability function and shall clearly define its responsibility for both policy and action.	SID 62-203 Section I Figures 1, 2, and 3	
It shall stipulate the authority delegated to this organization to enforce its policies and assure necessary action.	SID 62-203 Section I	
Line organization responsibilities and the relationships between line, service, staff, and policy organizations for reliability shall be identified.	SID 62-203 Section I Figures 1 and 2	
3.3.3.2 When this specification is called out as part of an initial procurement package (request for bid or proposal), the contractor's reliability program plan, in accordance with the above requirements, shall be submitted as a separate and complete entity within the contractor's proposal.		Not applicable
3.3.3.3 When this specification is negotiated into an existing contract, the contractor reliability program plan, in accordance with the above requirements, shall be submitted so as to be received by the procuring activity not later than the date specified in the negotiated contract change.	SID 62-203 Appendix E	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
3.4.1 Program Implementation.	SID 62-203 SID 62-109 SID 62-1405	
3.4.2 Program Review. The program shall be organized and scheduled to permit the contractor and the procuring activity to review the status of the reliability program, including results achieved, at preplanned steps. The program shall be revised and updated periodically to reflect changes in requirements or activities and shall be subject to contract negotiation. The contractor shall conduct continuous review as part of the comprehensive reliability program. All information, such as predictions of reliability, results of reliability design review, experience and test results on parts, components, assemblies, and the total system, including human performance, shall be used to assess reliability with the relative dependence on the various sources changing as the program proceeds to reflect the most accurate assessment possible.	SID 62-203 Sections I* and V Appendix E SID 62-203 Introduction SID 62-203 Sections I, IV, and V SID 62-203 Sections IV, V, and VIII SID 62-1405	

*Reliability and Milestone Status

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
3.4.3 Periodic Reporting. A reliability program activity and status report shall be submitted at intervals not to exceed three months and shall be negotiated with the procuring activity. The information submitted in these reports shall be for management review and program control. These reports may be combined with other program documentation provided all pertinent reliability information is contained or summarized in one report, or section of a report, and supporting information is adequately cross-referenced and readily available. The following notation shall appear in the upper right-hand corner of the form containing the program activity and status reports: Form Approved, Budget Bureau No. 21-R-151.2.	SID 62-203 Appendix E NAS9-150 Exhibit I SID 62-109-3	
3.5.1 Supplier and Subcontractor Reliability Programs. The contractor shall be responsible for assuring that suppliers' and subcontractors' achieved reliability levels are consistent with over-all system requirements. Contractors shall be responsible for determining the applicable portion of this specification to be included in subcontracts and purchase orders. The contractor shall impose upon the supplier and subcontractor quantitative specifications (using military specifications where possible), acceptance criteria, and contractual	SID 62-203 Section VI SID 62-203 Section VI	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
requirements for reliability of their products and shall maintain adequate channels of communication with all suppliers. The reliability program of the contractor shall contain necessary provisions for surveillance of the supplier and subcontractor reliability activities to assure satisfactory performance, assist him in problem solution, and provide feedback to him for corrective action, as necessary. The surveillance shall consist of such items as maintaining a supplier selection program, based upon review of the supplier's reliability program, quality control system, examination of his facilities, and past performance, to assure that the suppliers are capable of attaining and maintaining the required level of performance, including reliability. Records of each supplier's performance shall be maintained and reviewed with him periodically	SID 62-203 Sections VI and VIII Appendix F SID 62-203 Section VI Appendix F SID 62-1405 SID 62-154 SID 62-203 Sections VI and VIII SID 62-154	
3.5.2 Reliability Indoctrination and Training. The reliability program shall contain provisions to indoctrinate all employees whose work relates to the reliability of the product, so that they understand the value of their contribution. Emphasis shall be placed on human engineering aspects of all operations to minimize the	SID 62-203 Sections IX, X, and XI SID 62-154	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
degradation of reliability through human error. All employees, technicians, and skilled craftsmen who contribute significantly to reliability shall be subjected to continuing training to assure that their skills and knowledge keep pace with the advancing technology required to achieve optimum reliability. A major portion of the training program shall be oriented toward indoctrination of personnel in basic functions in newly developed reliability procedures, with the objective of ultimately accomplishing as much of the reliability task as possible by those functions. The contractor shall recommend training required for personnel in order that their work will not excessively degrade the reliability of the system.	SID 62-203 Section X SID 62-203 Sections IX, X, and XI	
3.5.3 Human Engineering. The reliability program shall apply the principles of human engineering in all operations during manufacture, test, maintenance, and operation of the system or subsystem where personnel are involved. The design shall incorporate those human engineering features that minimize the possibility of degrading reliability through human error. Contractors' human engineering personnel shall participate in the approval of all designs and proposed tests to assure that the principles of MIL-STD-803 have been incorporated in design and are reflected in test plans.	SID 62-203 Sections IV and XI	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
3.5.4 Statistical Methods. The contractor's reliability program shall incorporate optimum utilization of statistical planning and analysis. This shall include the application of such methods as design of experiments, analysis of variance, and other methods particularly suited to the design and development phases and the use of statistical quality control methods in the manufacturing process. When using failure rate data for system reliability or for parts, subassemblies, assemblies, etc., an appropriate statistical distribution function and a mathematical model shall be used to determine the probability of a system and subdivisions thereof meeting the respective individual reliability requirements.	SID 62-203 Sections III, VII, and X Appendix B SID 62-1405 SID 62-154 SID 62-203 Sections II and III	This shall include the application of such methods as sequential analysis, life testing, stress and strength distribution function, performance regression and correlation analysis, and other methods particularly suited to the design and development phases and the use of statistical quality control methods in the manufacturing process.
3.5.5 Effects of Storage, Packaging, Transportation, Handling, and Maintenance. The contractor shall determine the effects of storage, packaging, transportation, handling, and maintenance on the reliability of the product. He shall design the product to withstand these effects to the extent practicable, and any special storage, packaging, transportation, handling, and maintenance requirements that must be applied during the product's life shall be made known to the procuring activity.	SID 62-203 Section XII	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
3.6.1 System Reliability Requirements. The contractor shall establish reliability objectives and requirements, as applicable, for the system in a manner compatible with the design analysis, as specified in MIL-W-9411 or as otherwise specified in the contract.	SID 62-203 Section II	Delete reference to MIL-W-9411. MIL-W-9411 with amendments is a general specification for aeronautical weapon and support systems employing piloted aircraft, guided missiles, and ground electronics. Section 3.2.1. Weapon System "design analysis" is not applicable to the Apollo program.
3.6.1.1 Requirement Formulation Phase. Reliability shall be treated quantitatively in system studies as feasibility, parametric, and preplanning studies (but not necessarily in exploratory studies) performed during requirement formulation for new system programs.	SID 62-203 Section II	"Reliability requirements are to be replaced by "reliability objectives."
One of the objectives of studies in this phase is the definition of system reliability requirements which are realistic and that, when considered in combination with all other pertinent design factors, shall optimize the balance between military effectiveness and total resources cost.	SID 62-203 Section II	Reference to "military effectiveness" is not applicable.

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
3.6.1.2 Design and Development Phase. Unless otherwise specified in the contract, the reliability to be achieved with specified articles shall be regarded as minimum requirements. The minimum acceptable reliability requirements for all major equipments of the system shall be determined and included in appropriate sections of the aerospace system specification. These shall be established as firm contractual requirements.		Not applicable. There are no contractual reliability requirements during this phase.
Quantitative values of reliability for specified articles shall be estimated during the development phase. These values shall be negotiated and firmly established as a result of studies under 3.6.1.1 and in accordance with 3.3.3.	SID 62-203 Sections II, III, VI, and VII	Delete last sentence. Reliability numerics apportioned by NASA to contractor furnished equipment are continuously reapportioned to items and subsystems within these GFE.
These quantitative reliability requirements shall be established at a contractually specified control point prior to release of design of specified articles.	SID 62-203 Sections II and III	Delete. Reliability numerics are objectives only. No assessment of achieved reliability can be made prior to design release.

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
3.6.2 Parts Reliability. Maximum practicable utilization of available data and control information facilities shall be made to avoid needless duplication of testing.	SID 62-203 Sections III and VII SID 62-1405	
3.6.2.1 Parts Reliability Data. Analysis should be made of the environmental conditions associated with the reported failure rates. After normalizing and allowing for differences in the environmental and performance requirements of the parts, failure rate estimates, with confidence limits when practicable, should be made from the gathered data.	SID 62-203 Sections VII and VIII	Omit "confidence limits."
3.6.2.2 Parts Reliability Improvement Program. Preliminary reliability predictions for the equipment under development shall be made based upon environmental conditions, operating time, and failure rates.	SID 62-203 Sections II and III	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
Where studies, data, and experience indicate a requirement for a separate reliability improvement program for standard or common usage parts, the contractor shall propose a program to increase the reliability of such parts to the required level to meet the system reliability requirements.	SID 62-203 Sections II and III	Replace "requirements" with "objectives."
3.6.3 Reliability Requirement Studies. The reliability program shall provide for preliminary and continuing studies to validate specified requirements and form the basis for revising the quantitative reliability requirements for the system, applicable subsystems, and, as necessary, components and parts.	SID 62-203 Sections I, II, IV, and VIII	Replace "requirements" with "objectives."
Apportionment of reliability shall be accomplished by analyzing the importance (effect of failure) of the system elements, complexities, and functions including, as applicable, alternate modes of operation.	SID 62-203 Section II	
These studies shall include definition of functional performance limits, time of operation, and environmental conditions of operational use under which achievement of reliability will be demonstrated.	SID 62-203 Section II	Delete underscored words. Reliability demonstration is not a contractural requirement.

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
Progressive reliability goals shall be established for each major phase of a program and for phases with program review points. The detailed approach used in defining requirements and establishing feasibility shall be appropriately covered in the program description and subsequent periodic reports.	SID 62-203 Sections II and IV SID 62-203 Section II	Ultimate LOR objectives are defined by NASA. Interim objectives are not applicable.
3.6.4 Reliability Design Principles. The reliability program shall include provisions to assure that reliability principles are considered in the design.	SID 62-203 Sections III and IV Appendix C	
3.6.5.1 Specifications and Standards. Specifications and standards shall be established for use in manufacturing and in source or receiving inspection. This shall include the establishment of a classification of characteristics for selected items in accordance with MIL-W-9411. The contractor's procedures, however shall assure that acceptance criteria are compatible with the latest drawing change or specification issue, properly authorized.	SID 62-203 Sections IV and IX SID 62-154 SID 62-154 SID 62-203 Section XIII SID 62-154	Delete reference to MIL-W-9411. Classification of characteristics is not applicable.
3.6.5.2 Manufacturing Personnel Job Tasks. The manufacturing processes shall be broken down to a	SID 62-203 Sections IX and XI	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
level of complexity and skill level requirement which can be performed by personnel with a degree of thoroughness and workmanship that retains the reliability of the item.		
3.6.6 Reliability Considerations for Engineering Changes. When design changes or changes in requirements are dictated, the change shall take into consideration the effect on the reliability of the system.	SID 62-203 Sections IV and XIII Figure 25	
4.0 QUALITY ASSURANCE PROVISIONS 4.1 The supplier is responsible for the performance of all inspection requirements as specified herein. Except as otherwise specified, the supplier may utilize his own facilities or any other inspection facilities and services acceptable to the Government. Inspection records of the examinations and tests shall be kept complete and available to the Government as specified in the contract or order. The Government reserves the right to perform any of the inspections set forth in the specifications where such inspections are deemed necessary to assure supplies and services conformance to prescribed requirements.	SID 62-154	
4.2 Reliability Assurance. The reliability program plan, the associated data, and the demonstrated results	SID 62-203 Section V Appendix E	Replace "demonstrated" with "assessed." Reference Exhibit I as defining documentation requirements.

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
shall be submitted for review to appropriate activities in accordance with the terms of the contract.		
4.2.1.1 a. The reliability program shall include provisions for reliability review and evaluation by the contractor of significant designs before they are finalized.	SID 62-203 Section IV	
Procedures shall be incorporated to make use of a design checklist for reliability.	SID 62-203 Section IV Appendix C	
Test and failure data shall be used for corrective action as early as possible in the design phase.	SID 62-203 Section VIII	
The design review will include a detailed examination of the design documents, drawings, and specifications.	SID 62-203 Section IV	
b. The design review shall be participated in by appropriate personnel from the contractor's reliability organization; approval shall be denoted by a signature approval of each review by such personnel.	SID 62-203 Section IV	
c. Design review and evaluation shall be continuing in nature to provide for the earliest possible detection of any potential failure modes.	SID 62-203 Section IV	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
d. The contractor shall prepare and expeditiously process design changes which will prevent the recurrence of failure or which will otherwise enhance the reliability of the system.	SID 62-203 Sections IV, VIII, and XIII	
A system shall be established and maintained by the contractor to assure adequate control of specifications, drawings, and technical requirements and all changes thereto in order to establish and maintain configuration control.	SID 62-203 Section XIII SID 62-154	
e. The review of the design shall be made against previously defined qualitative and quantitative standards and the results of the review documented.	SID 62-203 Section IV	
4.2.1.2 Development Testing Program. A planned and scheduled program of functional testing and environmental determination and testing of equipment shall be conducted during design and development phases to estimate reliability achieved and to provide for feedback of data to be used as a basis for making reliability improvements. All equipment items of the system determined by the reliability studies to have a significant bearing on the inherent reliability shall be tested as early as practicable in the development program, unless proof of adequacy can be substantiated by other available data, to establish at least tentatively that the item is suitable for the application of the system.	SID 62-203 Section VII SID 62-1405 SID 62-109	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
The reliability test procedures of Specification MIL-R-26667 shall be used wherever applicable. Where these tests procedures are not applicable, the contractor shall submit a description of the test procedures that he plans to use.	SID 62-1405 SID 62-109	Replace "procedures" with "plans"
A current record of the results shall be maintained	SID 62-1405	
This program shall make use of evaluation or measurement obtained during development testing.	SID 62-203 Section VII SID 62-1405	
All test data shall be retained for a period of 2 years. The test data shall be made available to Air Force data collection activities, such as the Interservice Data Exchange Program (IDEP).	SID 62-203 Appendix E SID 62-109	Delete reference to "Air Force" and substitute "NASA specified." Exhibit I of NAS9-150 defines requirements.
4.2.1.3 Maximum Preacceptance Operation. The contractor shall establish and maintain a current list of items having critical useful lives (total operating time or operating cycle) in their application in the contractor's product.	SID 62-203 Sections IV and V Appendix C SID 62-1405	
He shall insure that each such item has its total operating time or number of equivalent operating cycles recorded, starting with and including its initial functional test, whether at the contractor's facility or a supplier's facility.	SID 62-203 Section III SID 62-1405	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
For each such item and within 30 days of its identification by him, the contractor shall propose for approval a maximum allowable operating time or number of equivalent operating cycles that is not to be exceeded prior to acceptance of the contractor's product. Upon mutual agreement between the procuring activity and the contractor, any item may be dropped from the above list, or its limit revised, when changes in the item's useful life indicate the need for such revisions.	SID 62-154	Not applicable. Requirements of NPC 200-2 shall govern.
4.2.1.4.1 Demonstration Plans. A general plan for demonstration of achieved reliability at a specified point in time, including estimated number of test articles and a qualitative estimate of the confidence level, shall be prepared by the contractor and submitted as part of the detailed design proposals. The general plans for demonstration of reliability shall include, as appropriate, trade-off curves showing number of test articles or cost versus confidence and will consider testing at the system, major element level, such as a flight vehicle and major subsystem or component levels separately and in combination, as applicable.	SID 62-203 Appendix E SID 62-1405 SID 62-109 SID 62-1405	Delete "as part of the detailed design proposals" and substitute "in accordance with contractual requirements." Replace the word "demonstration" with "assessment" and delete the reference to "confidence levels."

MIL-R-27542 (USAF) Requirement	Implementing Document	Comments
Demonstration plans shall be included in the performance demonstration procedures submitted as specified in the contract. The specific plans for demonstrating achieved reliability shall include any revisions to data in the general plan and the conditions and ground rules for deciding whether a test shall be classified as a success or failure or shall be excluded due to invalid test data. They shall be submitted by the contractor for review and approval by the Air Force as scheduled in appropriate contractual documents.	SID 62-203 Appendix E SID 62-1405 SID 62-203 Appendix E	Replace "demonstration" with "assessment." Delete "approval" Delete "Air Force" and substitute "NASA." Reference Exhibit I as "appropriate contractual document."
4.2.1.4.2 Reliability Contract Compliance Considerations. The point or points that are to constitute demonstration or contract compliance shall be established and incorporated in the contractual documents, unless otherwise specified in the contract. Detailed plans for conducting a reliability demonstration shall be submitted not later than 60 days prior to the date established for the demonstration to begin.		Delete in its entirety. NASA Technical Requirements Exhibit I shall govern. Delete "reliability demonstration." This is not a contractual requirement.

MIL-R-27542(USAF) Requirements	Implementing Document	Comments
4.2.1.4.3 Conditions of Test. The test conditions shall be as described in the specification(s) for the item(s) being tested. The following general rules for go-no-go type test apply equally well to electronic and mechanical equipment. In general, these rules shall apply to measurement of reliability for <u>demonstration</u> purposes, unless other rules are specified by the contract or proposed by the contractor and approved by the procuring activity. They do not necessarily apply to all testing used in achieving reliability. a. Test Classified as Successes. A test shall be classified as a success if the operation complies with the following: (1) Objectives established for the specific test are attained. (2) Performance is within the specified limits. (3) Test duration is sufficient and is established as an adequate test for each system. b. Tests Classified as Failures. A test shall be classified as a failure if it does not meet all the requirements for success as given above and is not excluded for one of the following:	SID 62-109 SID 62-1405	Detailed test procedures shall be prepared on each item tested. These shall be transmitted to NASA in accordance with Exhibit I documentation requirements. Replace "demonstration" with "assessment."

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
(1) Excluded Tests. Due to various circumstances, it may be necessary to exclude certain tests or failure data from consideration in the reliability demonstration. (a) Pre-Excluded. Some tests may be excluded beforehand and their success or failure shall not be used for reliability evaluation. Examples are: 1. Tests conducted beyond the design duty cycle of the equipment which can cause deterioration of equipment characteristics. 2. Tests conducted at environmental conditions beyond design limits, singly or in combination. 3. Check or adjustment runs. If a failure occurs that is only a marginal deviation beyond specified limits and it is determined that the remainder of the system functioned properly, the test may be considered a success for the remainder of the system. However, provisions must be made for additional testing to prove out the deficient component and the test shall be counted as a failure for the complete system under test. (b) Post-Excluded. Some failures shall not be included when determining the reliability of the item; however, conditions for exclusion shall be defined before testing. Examples are: 1. Failures caused by instrumentation, test site delays, or other conditions that would not be present in an operational situation.		

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
2. Failures caused solely by the test equipment that is not considered part of the equipment being tested. 3. Failures caused by human errors in setup and operation of ancillary equipment used during the test that would not be present in the operational situation. 4. Failures resulting from deterioration of components used beyond their design life expectancy to accomplish tests on other portions of the system.		
4.2.1.5 Reliability Measurement. System reliability shall be computed, where practicable, for both operational standby and operation and shall be based on both attribute data of pre-established success and failure criteria and on failure rate data. The reliability of systems in the standby and continuous long-term operating conditions shall be computed on failure rate data or other data as applicable. The final reliability measurement results shall be stated in the same measurement units as the requirements.	SID 62-203 Sections III and VII SID 62-1405	Delete "requirements"; substitute "objectives."
4.2.2.1 Control of Processes. Manufacturing processes shall be controlled to assure that variations which occur during this phase shall not degrade the reliability inherent in the design below levels established in accordance with 3.6.1.2. The contractor's process control procedures shall be documented.	SID 62-203 Section IX SID 62-154	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
4.2.2.2 Production Monitoring. The contractor shall have a planned, controlled, and scheduled program for the testing of production items or samples of production items to detect unsatisfactory items and provide a measure of the achieved reliability. The program shall include investigation and analysis of failures during production. The contractor shall make maximum use of the data derived from these production tests to assure satisfactory workmanship and to maintain performance and reliability of production items. As required for the tests for reliability demonstration, the quantities of tests and items to be covered shall be negotiated to fit the needs of the particular contract. As production experience on the specific items is gained and retention of reliability is proven, revision of the test and sampling procedures can be considered.	SID 62-1405 SID 62-154 SID 62-203 Section VIII SID 62-1405 SID 62-1405	 Substitute "assessment" for "demonstration."
4.3 Failure Reporting, Analysis, and Feedback System a. The contractor shall have a system for collecting, analyzing, and recording all failures that occur in-plant, as well as those that occur at test or installation sites, and all other significant reliability data, such as operating	SID 62-203 Section IV SID 62-203 Section VIII	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
time, cycles, and population during those phases of the program in which the contractor has primary responsibility. The scope of this program shall be defined in the contract.		Shall be defined in contractor's reliability program plan (SID 62-203)
The contractor shall describe his failure reporting system, including flow charts, for analysis, feedback, and corrective action as a part of the program plan. Analysis and recording of all failures shall differentiate between, but not be restricted to, those due to equipment failure and those due to human error in handling, transporting, storing, maintaining, and operating the equipment.	SID 62-203 Section VIII	
The systems shall include reporting of data on accumulated operation time or operation cycles on specified components of the systems that are time or operation cycle sensitive. The failure reporting system shall be designed to be compatible with the Air Force reporting system (see 6.2.13) so that as the system nears the operational inventory phase, transition to the Air Force failure reporting system can be		Failure reporting system shall be compatible with NASA requirements (AFM 66-1 is not applicable).

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
accomplished with the minimum disturbance and maximum continuity of effort. Requirements for any special supplementary reporting by the using service or the contractor during field use shall be as specified in the contract.		
The data shall be analyzed and transmitted to the design or manufacturing activity, as appropriate, and to other agencies as specified in the contractual document.	SID 62-203 Appendix E	
The failure reporting system shall include provisions to assure that effective corrective actions are taken on a timely basis to reduce or prevent repetition of the failures.	SID 62-203 Section VIII	
b. The contractor shall commence failure reporting on operating equipment at receiving inspection, at a vendor's plant in final assembly checkout, or during acceptance testing. Machinery rejects, defective castings, defective wire, or other faults found prior to assembly shall not be reported. Failure of electrical, mechanical, or chemical devices which are not a combination of two or more elements of the type normally not repairable except by manufacturer before their incorporation into an assembly shall not be reported. An unscheduled adjustment, other than a calibration made during other maintenance because of convenience, shall be defined as a failure for reporting purposes.		Delete paragraph b in its entirety. Scope of S&ID failure reporting activity shall be in accordance with the Reliability Program Plan (SID 62-203) and NPC 200-2.

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
c. The contractor shall periodically submit failure report summaries on systems as specified in the contract. Normally, these summaries will include as a minimum the following information: (1) Failure and usage data report. (2) Failure analysis report. (3) Progress reports as specified by the Air Force.	SID 62-203 Section VIII	Delete para. c. in its entirety and substitute "the contractor shall submit monthly failure report summaries on systems specified in Exhibit I."
d. The failure report forms utilized by the contractor contain the following minimum items, when applicable: (1) Report number. (2) Initial report number. (3) Reporting activity. (4) System type, model series. (5) System serial number. (6) Equipment type, model designation, model number. (7) Equipment serial number. (8) Failed item part number. (9) Failed item serial number. (10) Failed item name. (11) Failed item manufacturer. (12) Failed item reference designation. (13) Next assembly part number. (14) Next assembly serial number. (15) Next assembly name. (16) Next assembly manufacturer. (17) Next assembly reference designation.	SID 62-203 Sections V and VIII	

MIL-R-27542(USAF) Requirement	Implementing Document	Comments
(18) Replacement part number. (19) Replacement serial number. (20) System number. (21) Date of failure. (22) Operational usage at failure or removal. (a) Hours, minutes, seconds. (b) Cycles. (c) Calendar time. (d) Miles. (23) Failed item discovered during. (24) Repair or disposition action. (25) Replacement. (26) Severity of failure. (27) Cognizance. (28) Analysis required. (29) Description of trouble. (30) Disposition. (31) Reason for failure/removal. (32) Disposition approval signatures. (33) Failure analysis performed. (34) Found serviceable by repair activity. (35) Final disposition of repaired item. (36) Final disposition signatures.		
6.2.13 Air Force Reporting System. The Air Force reporting system is described in AFM 66-1. Application for copies should be directed to the Air Force representative assigned to the contractor's plant.		Not applicable. See Exhibit I and NPC 200-2.

NPC 200-2

REQUIREMENTS AND DEVIATIONS

NPC 200-2 Requirement	Implementing Document	Comments
1.1 These requirements include the establishment and maintenance of an effective quality program from design conception and development to delivery of articles of satisfactory quality level meeting the intended design.	SID 62-203	
1.2 This publication is applicable, when invoked by reference in the contract, to NASA space system prime contracts. It also applies to those major subcontracts to which its provisions are pertinent as determined by the cognizant NASA installation or by the prime contractor.	SID 62-203 Section VI	
1.4 The quality assurance provisions herein are intended to aid in achieving the required reliability of the complete space systems, launch vehicles, spacecraft, or ground support systems involved. Detailed reliability requirements will generally be contained in the contract work statement. Certain requirements herein, such as testing, may be considered common to both quality and reliability assurance. The contractor's quality control program shall be planned and used in a manner to effectively support the contractor's reliability program.	SID 62-203 SID 62-1405	
2.1 Any changes required to improve component, subsystem, or system performance without compromising quality or reliability shall be incorporated at the earliest practical point in development and fabrication.	SID 62-203 Section IV	
4.2.1 The contractor shall perform design review of drawings, specifications, and technical documentation to establish the characteristics which determine the quality and reliability of	SID 62-203 Section IV Appendix C	

NPC 200-2 Requirement	Implementing Document	Comments
the system, and to provide criteria to judge conformance of these characteristics. The contractor shall document design reviews and make such documentations available to the NASA installation and its designated representative. The contractor shall ensure that drawings, specifications, and technical documents contain adequate requirements for determining and controlling the quality of all items purchased or produced by the contractor. Such requirements shall be related to all phases of the system development including design, fabrication, testing, and end use. In detailing quality requirements, documents shall include: a. Identification of the article, b. Characteristics determined to influence quality, c. Inspection and test methods (including specific test equipment, environmental conditions, and sample size, as applicable). d. Conformance limits.	SID 62-109 Quality Control Plan SID 62-154	Exhibit I takes precedence
4.2.2 The design review shall include specific actions to maximize the use of parts and components which have been qualified as meeting the performance, reliability, and quality requirements of the contract. Feedback of information from previous experience with similar or related designs is a necessary input at this stage of the system development. The design review shall include application of any preferred parts lists cited in the contract or required to be established by the contractor to: (a) eliminate from the design parts known to be inadequate, and (b) to aid in planning part and component testing and screening.	SID 62-203 Sections III, IV, and V	

NPC 200-2 Requirement	Implementing Document	Comments
4.3.1 Qualification tests of all parts, components, sub-assemblies, and higher levels of assembly shall be performed to demonstrate the design is inherently capable of meeting the established requirements. Tests shall be designed to: a. Locate significant failure modes, b. Determine the effects of varied stress levels, c. Determine the effects of combinations of tolerance and drift of design parameters, and d. Determine the effects of combinations and sequences of environments. Destructive tests and an inspection of disassembled articles shall be included as appropriate. The contractor shall document and submit qualification test procedures in accordance with paragraph 7.3.1 and the contract. These procedures shall be statistically designed where advantageous to obtain the maximum of useful information. Data shall be submitted as specified in Section 14.	SID 62-203 Section VII SID 62-1405	Substitute "assess" for "demonstrate." Detailed test procedures, data and reports shall be prepared on each item tested. These shall be transmitted to NASA in accordance with Exhibit I.
4.3.2 Qualification tests of parts, components, and sub-assemblies shall be appropriate for the system performance, environments, and associated time requirements.	SID 62-109 SID 62-1405	

NPC 200-2 Requirement	Implementing Document	Comments
4.3.3 These qualification tests shall demonstrate, analyze, and evaluate system and subsystem effectiveness, interaction, integration, and compatibility under conditions which simulate actual end-use to the highest practical degree. Data shall be submitted as specified in paragraph 14.2.	SID 62-109 SID 62-1405	Substitute "assess" for "demonstrate" and delete the word "effectiveness." Delete the last sentence. Data requirements and submittal shall conform to Exhibit I.
4.3.4 Qualification tests performed on identical items prior to or outside the scope of the contract may be accepted at the discretion of the NASA installation to reduce requalification testing. Actual test data, environments, and procedures for such tests shall be made available to the NASA installation when the qualification test procedures are submitted. Qualification tests shall be repeated at intervals specified by the NASA installation and mutually agreed upon by NAA/SID.	SID 62-109 SID 62-1405	Requalification will be negotiated as part of CCA or included in MCR requirements.

NPC 200-2 Requirement	Implementing Document	Comments
4.4 Materials, processes, and design parameters shall be so identified in the design documentation that the engineering features to be evaluated may be associated with the particular articles. Each article, including parts and components, shall be identified by a unique part number and serial or lot numbers Certain articles, such as rivets, will not be serialized or identified by lot numbers after fabrication, provided that selection of such are approved by the NASA installation or its designated representative. These identification numbers shall be consistent with the engineering drawing and change control system used throughout the contract. When the contract requires mechanized or electronic processing of data for distribution, the identification numbers shall be suitable for such processing.		Reference appropriate I and T documents.
5.1 The contractor shall assume the responsibility for the adequacy and quality of all purchased materials, supplies, and services unless otherwise directed by the contracting agency in writing. This responsibility includes: (1) Selection of qualified procurement sources (2) Transmission of all design, reliability and quality requirements to procurement subcontracts and purchase orders (3) Effective provisions for early information feedback and correction of deficiencies	SID 62-203 General SID 62-154	

NPC 200-2 Requirement	Implementing Document	Comments
(5) Providing technical assistance and training to suppliers when necessary to achieve desired reliability and quality levels.		
5.3.1 Basic technical requirements – All drawings, engineering orders, specifications, quantitative reliability requirements, test and inspection procedures, special inspection and test equipment, and the latest applicable revision status shall be referenced and made available as necessary.	SID 62-203 Sections V and XIII SID 62-1405 SID 62-154	Replace "requirements" with "objectives."
Identification, preservation, and packaging — Requirements for adequate identification, special preservation, and transportation packaging required to preserve the quality of the article shall be referenced.	SID 62-203 Section XII	
Age control materials and articles having definite characteristics of quality degradation or drift with age and/or use shall be marked to indicate the date and test time or cycle the critical life was initiated or the date and test time or cycle at which useful life will be expended. Variables data shall be recorded and maintained. The supplier or contractor shall insure removal of such materials on a scheduled basis.	SID 62-203 Sections V and VIII SID 62-154	
Resubmission of rejected material – All items rejected by the contractor and subsequently resubmitted by the supplier to the contractor shall bear adequate identification of such resubmission either on the items or the supplier's shipping document. Reference shall be made to the contractor's rejection	SID 62-203 Section VIII SID 62-154	

NPC 200-2 Requirement	Implementing Document	Comments
document and evidence given that the causes for rejection have been corrected. Articles of supplier design — The supplier shall notify the contractor of any proposed changes and obtain approval of the change from the contractor before making the change. Appropriate identification of those items on which the change is incorporated shall be required.	SID 62-203 Section XIII SID 62-154	
5.8 The contractor shall maintain a system to feedback rapidly to suppliers the information necessary for correction of deficiencies detected during any phase of inspection, test, assembly operation, final checkout, or use of the purchased article. The system shall meet the corrective action requirements of paragraph 14.3.	SID 62-203 Sections V and VIII SID 62-154	
5.9 The quality capabilities of each supplier shall be objectively evaluated and documented by the contractor. Preferred source lists based on these evaluations and any preferred parts lists cited in the contract shall be made available to and used by the group responsible for procurement in the selection of procurement sources as required in paragraph 5.2.	SID 62-203 Section III SID 62-154	
5.10 The contractor shall assure early and continuous coordination of all inspection, test, and measuring instruments and correlation of inspection and test procedures between the contractor and his suppliers.	SID 62-109 SID 62-154	

NPC 200-2 Requirement	Implementing Document	Comments
7.2 The contractor shall provide documented criteria for acceptance of all articles produced by the contractor in accordance with contract requirements. These documents shall be available in advance of the time and at the place articles are offered for acceptance. Acceptance criteria include standards for judging whether or not the articles meet the drawing and specification requirements.	SID 62-109 SID 62-154	
7.3.1 Specific written inspection and test procedures, except those which are an integral part of detail manufacturing documents, shall be prepared and submitted for each inspection and test operation to be performed by the contractor or his subcontractors. These procedures shall include at least the following: (a) Identification of the article to be inspected or tested (e.g. part number, system involved, and nomenclature.) (b) The objectives of the inspection or test. (c) Measuring and test equipment to be used, specifying range, accuracy, and type. (Specify the particular scale, dial, or device to be observed. If recording type, indicate details of tape, film, or sensitized paper involved.) (d) Detailed operations to be performed by the test operator, including operational checks or preliminary calibration of test setup. (e) Exact method of inspecting or measuring, including necessary manipulation of controls on the article involved and on the measuring and test equipment.	SID 62-109 SID 62-154	

NPC 200-2 Requirement	Implementing Document	Comments
(f) Conditions that must be maintained during inspection and test, including ambient or environmental conditions and precautions to be observed to prevent damage to the item or instruments involved. (g) Criteria for passing or failing the test or for acceptance or rejection of the article, including reference to workmanship inspection standards. (h) Details of sampling plans to be used, if applicable. These inspection and test procedures shall be readily available to inspection and test personnel and shall be physically located at the applicable inspection or test station.		
7.3.2 Each characteristic to be observed shall be defined in terms of: the conditions which should exist at each examination point, the tolerance conditions under which the characteristic being examined may be considered acceptable, and the levels or limits of inputs or stresses. In the case of visual inspection, the optimum acceptable condition shall be well defined.	SID 62-109 SID 62-154	
11.1 The contractor shall prepare written procedures for preservation, packaging, handling, storage, and shipping to provide necessary protection of all articles throughout the scope of the contract to prevent damage, loss, deterioration, degradation, and substitution. The contractor's quality assurance organizations shall review all these procedures prior to their implementation. These procedures shall be made available to the cognizant NASA installation or its designated representative upon request.	SID 62-203 Section XII	

NPC 200-2 Requirement	Implementing Document	Comments
11.3 Articles subject to deterioration, corrosion, or damage in the packaged state shall be packaged in a manner and with such materials as necessary to prevent damage. Requirements for packaging shall consider conditions affecting the article while at the contractor's plant, transportation to destination, and the expected or specified conditions at destination. Packaging methods shall be established and documented by the contractor when the methods are not adequately covered by existing specifications. Packaging shall include means for indicating critical environments within the package, such as moisture content, temperatures, or gas pressure. When maintenance of specific internal or external environments are necessary, these shall be included in the packaging and necessary special instructions shall be provided on the exterior of the package.	SID 62-203 Section XII	
11.4 The contractor shall provide special handling for articles sensitive to handling damage. During fabrication and processing, special carts, boxes, containers, and transportation vehicles shall be utilized as necessary to prevent damage due to handling. All installation and test sites shall be provided copies of special handling instructions to ensure safe and adequate handling.	SID 62-203 Section XII	
12.1 Statistical planning, analysis, test, and quality control procedures may be utilized by the contractor whenever such procedures are advantageous in maintaining required control and in obtaining a maximum of useful information from a minimum of data, time, and personnel.	SID 62-109 SID 62-154	

NPC 200-2 Requirement	Implementing Document	Comments
12.3 Sampling plans may be used whenever tests are destructive or records, inherent characteristics of the article, or the noncritical application of the article indicate that a reduction in inspection or testing can be achieved without jeopardizing quality. When the contractor employs sampling inspection, it shall be in accordance with applicable military standard sampling plans (e.g. from MIL-STD-105, MIL-STD-414, or Handbook H108). Application of military sampling plans shall be subject to the disapproval of the cognizant NASA installation. If the contractor proposes to use an alternate sampling plan, the lot size, sample size, acceptance criteria, and operating characteristic curve shall be submitted to the cognizant NASA installation for review as required by paragraph 2.2 and appendix A. The standard military sampling plan or approved alternate sampling plan, selected or designed, shall provide an average quality level, which is in appropriate proportion to the reliability required of the involved end item, subsystem, or equipment thereof.	SID 62-154	Reference Exhibit I for special sampling plan, submittal requirements
13.1 The contractor shall develop, implement, and maintain training programs for quality assurance, purchasing, manufacturing, and other personnel who may have an effect upon or who are responsible for the determination of quality. Training programs shall include, as needed, familiarization with space parts, components, equipment and systems, inspection and test equipment, and instruction in techniques and methods for procuring, processing, fabricating, inspection, test, checkout, quality control, statistical quality control, packaging, and handling. Particular emphasis shall be given to the function and mission of the end item, to new articles,	SID 62-203 Section X SID 62-154	

NPC 200-2 Requirement	Implementing Document	Comments
and to new or sensitive fabrication processes or materials. The training programs shall include sufficient training to assure personnel proficiency and a means of determining the proficiency of persons completing the courses. Inspector training programs shall, where practical, include the inspection of appropriate articles with known deficiencies in order to evaluate the inspector's proficiency. Training needs shall be periodically assessed to determine requirements for additional training. The responsibility for determining the need and developing curricula for training of contractor personnel relating to all quality assurance aspects shall rest with those organizational units responsible for the assurance of quality.		
13.2 Contractor personnel responsible for controlling special processes or for performing fabrication and inspection operations of a specialized nature having a significant effect upon the quality shall be certified. Certification by the contractor or the government inspection agency may be reviewed or repeated by the cognizant NASA installation to verify the adequacy of such certifications. Certification of personnel for these processes, materials, or operations (such as welding, soldering, wiring, radiography, magnetic particle, dye penetrant and bonding) shall include necessary training followed by a testing procedure to assure the proficiency of each individual. Personnel satisfactorily completing the training and the required tests shall be given a card, badge, or similar evidence of his certification to be carried on his person while performing those duties. Records shall be maintained of	SID 62-203 Sections IX, X, and XI SID 62-154	

NPC 200-2 Requirement	Implementing Document	Comments
all individuals certified, indicating the date of their last certification. The period of effectivity for all certifications shall be specified, and each individual shall be recertified at the end of such period through retesting. Persons failing the retest shall be removed from these operations and provided with additional training, as required, prior to recertifying the individual. Results of inspections, tests, and quality audits shall be used as indicators of the need for additional training and recertification of manufacturing and inspection personnel without regard for establishing recertification periods.		
14.1 Procedures and responsibilities shall be established by the contractor for the collection and analysis of all trouble, failure, and quality data resulting from testing, inspection, and usage of the articles procured or produced. These procedures and assigned responsibilities shall include effective follow-up to assure timely and adequate corrective action on all reported deficiencies, throughout all test programs by the contractor and all subcontractors, as well as including field, preflight and flight operations. Data shall be collected and analyzed to: (a) Provide an indicator of design and fabrication deficiencies so that early corrective action can be initiated. (b) Provide corrective and preventive action feedback information to various elements of the contractor's organization to develop, improve, and maintain required quality and reliability. (c) Provide management with quality trends.	SID 62-203 Sections V and VIII SID 62-154	

NPC 200-2 Requirement	Implementing Document	Comments
(d) Provide complete functional and performance history on all articles for use in design selection, qualification testing, and design improvements. (e) Evaluate quality aspects of specifications, drawings, and technical documents. (f) Determine the need for special investigations and analyses. (g) Establish the requirements for process control charts. (h) Provide subcontractor quality ratings and feedback information for quality improvement of purchased articles. (i) Determine the validity of inspection and test procedures, process controls, and sampling plans. (j) Provide engineering, purchasing, and fabricating personnel with information on actual quality levels. (k) Indicate the need for specific quality training. (l) Indicate the need for certification and recertification of personnel. (m) Indicate product producibility and variability of articles. (n) Establish and maintain a realistic list of limited and critical life articles.	SID 63-1388	Special investigation and analysis will be noted and negotiated with NASA.
14.2 Trouble, failure, and quality data on every part, component, equipment, and system shall be completely and accurately collected, processed, analyzed, and disseminated in a minimum of time to all pertinent areas within the contractor's organization, to the suppliers concerned, and to the cognizant NASA installation and its designated representative. The data required shall include, but is not limited to,	SID 62-203 Sections V and VIII	Reference Exhibit I as document of precedence.

NPC 200-2 Requirement	Implementing Document	Comments
that specified in this section and may be submitted in separate reports as generated.		
14.2.1 Narrative comments, recommendations, tabulations of pertinent data and summary of corrective action supplemented by graphs, photographs or exhibit shall be compiled into a Monthly Quality Status Report which shall be submitted for information in accordance with paragraph 2.2 and Appendix B. When the contract requires mechanized or electronic processing of data, the data shall be transmitted as specified and the Monthly Quality Status Report shall provide a summary of results, corrective action, narrative information, and recommendations.		The monthly quality report has been deleted per Exhibit I.
14.2.5 Operational data reported shall include a complete description of operating or mission objectives, operating time, numerical results obtained, anticipated and actual functional and stress conditions, complete and detailed failure data, including identification and description of part, component, or equipment that failed, the system or subsystem involved, conditions at time of failure, operating time to failure, mode of failure, date and geographical location of failure, how failure was observed, and recommendations.	SID 62-203 Sections V and VIII	
14.3 A program shall be established by the contractor to feed back information and take corrective action on all troubles, malfunctions, deficiencies, and failures discovered by the contractor, subcontractors, and government representatives during inspection and test at the plant, at test sites, and at launch sites and during flight operations. The contractor shall operate a failure analysis function with necessary laboratory facilities at his plant site and at the launch site, as specified	SID 62-203 Sections V and VIII SID 62-154	

NPC 200-2 Requirement	Implementing Document	Comments
in the contract. Failures and malfunctions occurring at the contractor's plant shall be analyzed at the plant, as practical; those occurring at the prelaunch operations site shall be analyzed at the site, as practical. Data reporting, analysis, and corrective action shall involve closed loops providing complete action for all phases of development, fabrication, test, and use of system hardware. The program shall be documented and, as a minimum, provide that the following steps be taken by the contractor: (a) Immediate notification to the applicable contractor's design, procurement, reliability, quality control, fabrication, and supplier organizations that corrective and preventive action is required. Critical failures or malfunctions (those affecting safety, mission, delivery schedule, or early effectivity, shall be so identified, giving priority handling, and immediately reported to the NASA installation and its designated representatives, as mutually agreed. (b) Analysis of the pertinent data and an examination of the deficient or failed articles to determine the nature and basic causes of deficiencies or failures. The deficient or failed articles shall be made available to the NASA installation or its designated representative at all times. The NASA installation shall be provided with samples of deficient or failed articles upon request.		Exhibit I takes precedence.

NPC 200-2 Requirement	Implementing Document	Comments
(c) Analysis of malfunctions, troubles, and failures traceable to human or operator error shall be made by persons skilled in human factors engineering. Analysis of malfunctions, troubles, and failures traceable to design, purchasing, fabrication, or inspection and test procedures shall be analyzed by engineering, reliability and quality control organizations, as pertinent. (d) Prompt corrective and preventive action. Also, documentation of the action taken or in process to correct existing deficiencies and minimize or eliminate future occurrences. (e) Rework of all affected articles in the plant, at test sites and at operating sites. (f) Review to determine the adequacy of the corrective action proposed or taken. (g) Notation of each deficiency in reports prepared by the contractor until adequate correction has been taken.		

APPENDIX I

GLOSSARY OF RELIABILITY TERMS

ACCESSORY. An item designed to supplement an assembly or set, contributing to the effectiveness thereof without extending or varying the basic function of the assembly or set. Same as ATTACHMENT.

ACCEPTANCE TESTS. Tests to determine conformance to design or specifications as a basis for acceptance.

ACHIEVED RELIABILITY. The system reliability evaluated at a designated point in time.

ARITHMETIC MEAN. The sum of a set of values, divided by the number in the set.

ASSEMBLY. A combination of parts or subassemblies that can be taken apart without destruction and that has no application or use of its own, but is essential for the completeness of a more complex item with which it is combined (e.g., IF amplifier, crystal filter).

ATTACHMENT. An item designed to supplement an assembly or set, contributing to the effectiveness thereof without extending or varying the basic function of the assembly or set. Same as ACCESSORY.

ATTRIBUTE. A qualitative characteristic of an item in contradistinction to a quantitative characteristic (e.g., a valve's position is an attribute but leakage rate is a variable).

ATTRIBUTES (METHODS OF). Measurement of quality by the method of attributes consists of noting the presence or absence of some characteristic (attribute) in each of the units in the group under consideration and counting how many do or do not possess it.

ATTRIBUTE TESTING. A test procedure where the characteristic being tested is classified qualitatively in accordance with existence or non-existence, rather than quantitatively.

AVAILABLE TIME. Time measured from the correction of a malfunction or the ending of preventive maintenance to the next succeeding malfunction or the next preventive maintenance action.

AVERAGE. A value that represents or summarizes some relevant features of a set of values. Commonly used to refer to arithmetic mean.

BINOMIAL DISTRIBUTION. A discrete distribution of one random variable having one parameter. Let f(x) be the probability of obtaining exactly x successes in n trials, and p be the probability of success in a single trial. Then

$$f(x) = \frac{n!}{x!\,(n-x)!}\, p^x (1-p)^{n-x} \text{ for } x = 0, 1 \ldots\ldots n$$

CASUALTY. Same as FAILURE

CATASTROPHIC FAILURE. A sudden change in the operating characteristic of an item resulting in a complete lack of useful performance of the item.

CHANCE FAILURE. Same as RANDOM FAILURE. Failures whose occurrence in any given interval of time is unpredictable.

CHECKOUT TIME. The time required to determine whether the performance characteristics of a system are or are not within specified values.

CHI-SQUARED FUNCTION. An incomplete gamma function that expresses a distribution of many independent standardized variables. The form of the chi-squared function differs for each number of degrees-of-freedom. Chi-square is the sum of squares of n independent normal variates divided by their common variance.

COEFFICIENT OF VARIATION. A relative measure of dispersion in a distribution. The standard deviation divided by the mean. This coefficient is very sensitive to errors in the means and is of limited use.

COMPONENT. A functional part of a subsystem or equipment that is essential to operational completeness of a subsystem or equipment and which may consist of a combination of parts, assemblies, accessories, and attachments.

COMPLEXITY RELATIONSHIP. The relationship between complexity and failure rate which can be expressed as $\lambda = nr_p$ where λ is the failure rate for an equipment containing n number of parts, each having the same probable failure rate r_p. For equipments containing many different types of parts each used under different conditions, thus yielding a different failure rate, the complexity relationship can be expressed by the equation

$$\lambda = n_1 r_1 + n_2 r_2 + \ldots\ldots n_p r_p$$

where

n_1 = Number of parts having failure rate r_1, etc.

n_p = Number of parts having failure rate r_p

CONFIDENCE. Quantitatively, the computed degree of assurance, or chance, that a given probability statement is true.

CONFIDENCE INTERVAL. A range of values that is believed to include, with a preassigned degree of confidence, the true characteristic of the lot or universe a given percentage of the time.

CONFIDENCE LEVEL. The degree of desired trust or assurance in a given result.

CONFIDENCE LIMITS. Extremes of a confidence interval within which the true value has a designated chance (confidence level) of being included.

CONSUMER'S RISK. Associated with any acceptance procedure or test, the consumer's risk is the chance of accepting an item that should be rejected.

CORRELATION. The interdependence between two occurrences which is expressed as a number between -1 and +1.

CRITICAL FAILURE. See FAILURE.

CUMULATIVE DISTRIBUTION FUNCTION. The distribution function F(x) of a variate X such that the function is equal to the total frequency of members with variate values less than or equal to x. In symbols,

$$F(x) = Pr(X \leq x) \text{ where } -\infty \leq X \leq x.$$

Similarly for p variates $X_1, X_2, \ldots, X_p$ the distribution function $F(x_1, x_2, \ldots x_p)$ is the frequency of values less than or equal to x_1 for the first variate, x_2 for the second variate, etc.

DEBUGGING. A reliability conditioning procedure that is a method of aging the equipment by operating it under specified environmental and test conditions in accordance with an established procedure in order to eliminate early failures and age or stabilize the equipment prior to final test and shipment. Also known as burn-in or infant mortality. See EARLY FAILURE PERIOD.

DEFECT. Any deviation of a unit of product from specified requirements. A unit of product may contain more than one defect.

DEFICIENCY. Same as DEFECT.

DEGRADATION FAILURE. A failure resulting from a gradual change in the performance characteristics of an item over a period of time.

DESIGN RELIABILITY. The probability of the equipment performing properly when manufactured with expected quality control, operated under contractually

stated conditions, utilizing supporting equipment and procedures in the manner intended, and with no degradation by personnel or personnel actions.

DESTRUCTIVE TESTING. Any test that results in destruction or drastic deterioration of an article so that it is rendered unfit for repair or service.

DEVICE. A general term used to represent any of the subdivisions of a system. Same as ITEM.

DISCRETE VARIABLE. A variable that can take only certain isolated values.

DISTRIBUTION. The relative arrangement of a set of numbers.

DOWN-TIME. The total time during which the system is not in condition to perform its intended function.

EARLY FAILURE PERIOD. That period of equipment life starting just after final assembly where equipment failures occur initially at a higher than normal rate due to the presence of defective parts and abnormal operating procedures.

ELEMENT. A general term meaning a substructure; e.g., a subassembly is an element of an assembly.

ENVIRONMENT. The aggregate of all the conditions and influences that affect the operation of equipment and components, e.g., physical location and operating characteristics of surrounding equipments and/or components, the temperatures, humidity, and contaminants of surrounding air, operational procedures, acceleration, shock and vibration, radiation, method of utilization, etc.

ENVIRONMENTAL RANGE. The range of environment throughout which a system or portion thereof is capable of operation at not less than the specified level of reliability.

EQUIPMENT. A general term for hardware other than airframe or structural elements. Usually applied only to hardware that performs some system function. It may refer to a single component or assembly or to a complete subsystem.

EXPECTED VALUE. Mean value, over the population of all possible values.

EXPONENTIAL FAILURE DISTRIBUTION. The distribution that results from a population with a constant failure rate. The cumulative distribution has the form

$$F(t) = 1 - e^{-\lambda t} = P_f \text{ (probability of failure)}$$

where

λ = Failure rate

t = Time

FAILURE. A cessation of ability to perform a specified function or functions within previously established limits. This requires that measurable limits be established to define satisfactory performance of the function. It is often desirable to categorize the failures within a system according to the severity of the resultant system defect. These categories are:

1. Critical (a reliability degrading failure with ramifications in crew safety)

2. Major (a reliability degrading failure that will influence accomplishment of the mission and mission objectives)

3. Minor (a failure with no ramifications in mission success or crew safety; one that influences the basic integrity of the equipment and constitutes a nuisance value or maintenance incident)

It is often desirable to categorize the failures within a system according to cause. These categories are:

1. Primary (a self-induced failure)

2. Secondary (a failure induced by human error or one that was induced by a failure in other equipment)

FAILURE RATE. The number of failures per unit time in specified equipment.

FAULT. Same as DEFECT.

FREQUENCY DISTRIBUTION FUNCTION. The frequency distribution function f of x for variate X is defined to be the derivative of the cumulative distribution function. It is the same as the probability density function only when the distribution concerned, is one of the probabilities. At points where $F'(x)$ does not exist, $f(x)$ is not defined. An equivalent definition is:

$$f(x) = \lim_{h \to o} \frac{1}{h} \Pr\left(x - \frac{h}{2} \leq X \leq x + \frac{h}{2}\right)$$

FUNCTIONAL PERFORMANCE TIME. The time during which an item is performing a specified function.

GAUSSIAN DISTRIBUTION. Same as NORMAL DISTRIBUTION

GROUP. A combination of modules, assemblies, and subassemblies that is a subdivision of a subsystem or system, but that is not capable of performing an operational function (e.g., antenna group, indicator group).

HAZARD. Same as FAILURE RATE.

HUMAN INITIATED FAILURE. Those failures that are traceable principally to some human action, either of commission or omission, occurring in any activity subsequent to design and manufacture.

INDEPENDENCE. One event is independent of another if the occurrence of the first does not affect the probability of the second occurring.

INFANT MORTALITY. Failures occurring during the debugging phase or early portion of equipment life.

ITEM. A general term used to denote one of a number of similar units, objects, test pieces, etc.

KURTOSIS. A statistical quantity that expresses the peakedness of a unimodal probability density function. The value of 3 is taken as standard for normal distributions.

LIFE CHARACTERISTICS. Life as a function of failure rate. Usually it is plotted showing three parts: (1) an infant mortality or debugging part; (2) a normal operating (constant λ) part; and (3) a wearout portion, i.e., the relationship that holds between the failure rate of equipment and operating or test time.

MALFUNCTION. A general term used to denote the occurrence of failure of a product to give satisfactory performance. It need not constitute a failure if readjustment of operator controls can restore an acceptable operating condition.

MARGINAL TESTING. A procedure for system checking that indicates when some portion of the system has deteriorated to the point where there is a high probability of a resultant system failure during the next operating period. (An example might be operation of the system with system heater voltage reduced by a given percentage to determine whether the system will continue to perform satisfactorily at that reduced voltage.) Thus, marginal testing is a form of prediction testing. It tests equipment under more severe conditions than are normally present and thus functions by causing it to become an observable failure. Alternatively, marginal testing is (1) a means of varying circuit or system parameters in such as way as to indicate

potential operational failures in a system, and (2) the means of altering circuit or system performance to render intermittent faults continuous, thereby simplifying troubleshooting.

MEAN. The mean (also expectation or average) of a random variate X (and of its distribution) is defined to be

$$\int_{-\infty}^{\infty} xf(x)\,dx$$

where f is the frequency function of x. If x is discrete, then its mean is

$$\sum_{\text{all } x} x \Pr(X = x)$$

where the summation is extended over all values which x assumes. (Usually integers.)

MEAN USE CYCLE TO FAILURE. Mean number of performance periods between failures.

MECHANISM OF FAILURE. The physical process that resulted in a part or equipment failure, e.g., the short was caused by contamination resulting from a poor hermetic seal. See MODE OF FAILURE.

MEDIAN. That value of the variate which divides the total frequency into two halves. As a partition value it may be defined for a continuous frequency distribution by the equation

$$\int_{-\infty}^{M} f(x)dx = \int_{M}^{\infty} f(x)dx = \frac{1}{2}$$

where M is the median value. For a discontinuous variate, ambiguity may arise which can only be removed by some convention. For a total frequency of 2N+1 items the median is the variate value of the $(N+1)^{th}$ item, for 2N items it is customery to take the average of the N^{th} and $(N+1)^{th}$ items.

MISSION TIME. The period of time in which a device must perform a specified mission task in a specified environment.

MODE. A mode of continuous random variable is a maximum of its frequency function. If f(x) is a frequency function, a mode is a value of x for which $df(x)/dx = 0$ and $d^2f(x)/dx^2$ 0.

MODE OF FAILURE. The physical description of the manner in which a failure occurs. Also, in analysis of design reliability, a description of the manner in which an equipment function can be affected by a failure.

MODULE. A combination of components, contained in one package or so arranged that they are common to one mounting, that provides a complete function or functions to a system and/or subsystem in which they operate.

MOMENTS. The mean values of a power of a variate. A moment about a particular fixed value, such as the mean value of a power of the deviation of the variate from that fixed value. In symbols, $m_k = \int_{-\infty}^{\infty} (x - \mu)^k f(x)dx$ and $m_k = \frac{1}{n} \sum_{\text{all } x} (x - \mu)^k Pr(X = x)$ for continuous and discrete variates, respectively.

MTBF (MEAN-TIME-BETWEEN-FAILURE). The total operating time accumulated by a population of identical equipment items, divided by the number of failures occurring in the time of observation. The operating time must include the time accumulated by items that did not fail, as well as the time accumulated by items that did fail.

MTTFF (MEAN-TIME-TO-FIRST-FAILURE). The average time to first failure of several items of equipment. It is used to determine the apparent approach of the equipment life characteristic to its random failure rate.

MTTF (MEAN-TIME-TO-FAILURE). Same as MTTFF.

NORMAL DISTRIBUTION. Same as GAUSSIAN DISTRIBUTION. A random variate X has a normal (also Gaussian) distribution with mean (μ) and standard deviation (σ) if its frequency function is such that

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(\frac{-(x - \mu)^2}{2\sigma^2}\right) \text{ where } -\infty \leq x \leq \infty$$

NORMALITY. The state of being perpendicular. The state of a variate having the normal probability distribution. The state of reduction to a common standard.

NORMAL OPERATING PERIOD. That period of time during which the equipment failure rate remains essentially constant.

NULL HYPOTHESIS. A negative proposition used for the purpose of a statistical test, e.g., the sample mean is not statistically representative of the parent population mean. The hypothesis which determines the type I error or producer's risk α.

OPERATING TIME. The time period between turn-on and turn-off of a system, subsystem, component or part during which time operation is specified. Total operating time is the summation of all operating time periods.

OPERATIONAL RELIABILITY. The probability that the system will give specified performance for the duration of a mission when used in the manner and for the purpose intended.

PART. One piece, or two or more pieces joined together, which is not normally subjected to disassembly without destruction of designed use.

POISSON DISTRIBUTION. A discrete random variate X has a Poisson distribution with mean $\lambda \geq 0$ if:

$$f(x) = Pr(X = x) = \frac{\lambda^x e^{-\lambda}}{x!}$$

for x = 0, 1, 2. . . . etc. The Poisson distribution may be regarded as the limiting distribution of a binomial.

POPULATION. The total collection of units from a common source; the total collection of units from a process, such as a production process. Also used in the sense of a "universe (or population) of observation." Universe, population, and parent distribution are synonymous terms.

PREVENTATIVE MAINTENANCE. A procedure of periodically checking and/or reconditioning a system to prevent or reduce the probability of failure or deterioration while in service.

PROBABILITY. The likelihood of the occurrence of any particular form of an event, estimated as the ratio of the number of ways in which that form can occur to the whole number of ways in which the event might occur in any form. Also defined as the limiting frequency in an infinite random series.

PROBABILITY DENSITY FUNCTION. A function giving the relative probability with which the variable can be expected to occur. Same as FREQUENCY DISTRIBUTION FUNCTION.

PROBABILITY OF FAILURE. The probability that an item will fail during a specified period of time under a specified environment.

$$P_f = 1 - P_s$$

where

P_f = Probability of failure

P_s = Probability of success

PROBABILITY OF SUCCESS. A numerical expression of reliability with the accepted nomenclature of P_s and a range from 0 to 1.0, indicating the extremes of impossibility or certainty. In other words, the probability of a given equipment performing its intended function or the given use cycle.

PROBABILITY OF SURVIVAL. Same as PROBABILITY OF SUCCESS.

PRODUCER'S RELIABILITY RISK. The risk of the producer (usually standardized at 10 percent) that a reliability acceptance test will reject a product when it is actually equal to, or better than, the specified value or reliability.

QUALITY. A measure of the degree to which a device conforms to specifications and workmanship standards. Its numerical rating is obtained by measuring the percentage defective of a lot or population at a given time.

QUALITY CHARACTERISTICS. Those properties of an item or process in the population domain that can be measured, reviewed, or observed, and that are identified in the drawings, specifications, or contractual requirement. Quality is measured by percentage defective of a lot or population at a given time.

RANDOM FAILURE. Failure whose occurrence in any given interval of time is unpredictable.

RANDOM SAMPLE. A sample in which each item in the lot has an equal chance of being selected.

RANDOM VARIABLE. A variable, either discrete or continuous, that can assume any one of a number of values, each of which has a fixed probability of occurrence.

RANGE. A statistical quantity describing the variance of a set of values. The difference between the largest and the smallest.

READINESS TIME. The time measured from the beginning of preparation of an operable system for use to the instant when the system begins to function in its intended fashion.

REDUNDANCY. The existence of more than one means for accomplishing a given task, where all means must fail before there is an over-all failure to the system. Parallel redundancy applies to systems where both means are working at the same time to accomplish the task, and either of the systems is capable of handling the job itself in case of failure of the other system. Standby redundancy applies to a system where there is an alternate means of accomplishing the task that is switched in by a malfunction sensing device when the primary system fails.

RELIABILITY (COMPUTED). The synthetic calculated probability of a system performing its purpose within specifications, based on estimates or tests of the reliability of its components.

RELIABILITY GOAL (OBJECTIVE). The product reliability which it is desired to achieve.

RELIABILITY INDEX. Figures of merit, such as ratios, factors, etc., used to denote relative reliability.

RELIABILITY. The probability of attaining specified performance under specified conditions for a specified period of time.

RELIABILITY TESTS. Tests and analyses, in addition to other type tests, which are designed to evaluate the level of reliability in a product, parts, or systems, and the dependability or stability of this level with time and use under various environmental conditions.

REPAIR TIME. Average time required to repair any item, discounting any time lost because of nonavailability of spares, tools, etc.

SAFETY FACTOR (DESIGN MARGIN, DERATING). The margin of conservativeness inherent in the application of component parts as a function of all stresses. There is usually a limited stress (or combination of stresses) at which part failure rate goes to infinity or to an unacceptable extreme. The degrees to which application-stress conditions are backed off from such a limit constitutes a safety factor from the catastrophic failure viewpoint. From the performance degradation viewpoint, a safety factor is represented by an adequate reserve of energy (as in the case of a battery) gain characteristic (trans-conductance) band-width, or other essential performance factors.

SAMPLE. A set of units of a product chosen to represent all units for inspection purposes.

SAMPLING PLAN. A plan for acceptance or rejection which gives the sample sizes to use and the criteria for acceptance or rejection.

"SCHMOO" PLOT. A graph of the output of a circuit under the various combinations of worst-chance voltage, temperature, etc., to determine marginal performance.

SEQUENTIAL TEST. A sequential test of a statistical hypothesis is a sequence of samples wherein, in effect, it is decided at each step in the sequence to accept the hypothesis, to reject the hypothesis, or to take an additional sample.

SET. A general term characterizing an item which has a complete function independent of being a substructure of a system. Same as EQUIPMENT.

SHELF LIFE. The length of time an item can be stored under specified conditions and meet specified requirements with a specified level of assurance.

SIGNIFICANCE LEVEL. Associated with a test of a statistical hypothesis, it is a predetermined, expected fraction of all cases of repetition of the test in which the hypothesis is rejected under the test even though it is true.

SIGMA LIMITS. The interval about the mean expressed in units of standard deviation. Assuming a normal distribution, two-sigma limits on each side of $\bar{x}$ would include about 95 percent of the population, and three-sigma limits would include about 99 percent of the population of measurements.

SKEWNESS. A statistical measure of the asymmetry in a distribution.

STANDARD DEVIATION. A statistical measure of the dispersion. It is the positive square root of its variance, and may be expressed:

$$\sigma = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - \bar{x})^2}$$

The standard deviation is also defined as the root mean square (RMS).

STANDARD TIME. The time during which a system has partial application of power and can be made to function usefully essentially instantaneously.

STATISTICAL ACCEPTANCE TEST. A procedure designed to determine, with a prescribed accuracy, whether a characteristic of a product is in conformity with acceptance criteria set forth for that product.

STATISTICAL TEST. A procedure used to determine whether or not observed values or quantities fit a hypothesis sufficiently well so that the hypothesis can be accepted.

STATISTICS. The collection, analysis, interpretation, and the presentation of numerical data where randomness of the data is a consideration.

SUBASSEMBLY. Two or more parts which form a portion of an assembly or a unit replaceable as a whole, but having a part or parts which are individually replaceable.

SUBSYSTEM. A major functional part of a system, usually consisting of several components, which is essential to operational completeness of the system.

SYSTEM. This term includes aerospace systems, weapons systems, support systems, command and control systems, their components, and all associated material.

SYSTEMATIC FAILURE. One which is resolvable by systematic means, such as design changes, improved workmanship, controls, etc.

TEST TO FAILURE. Testing conducted on one or more items until a predetermined number of failures have been observed. Failures are included by increasing electrical, mechanical, and/or environmental stress levels, usually in contrast to life tests, in which failures occur after extended exposure to predetermined stress levels. A life test can be considered a test to failure using age as the stress.

TROUBLE-SHOOTING TIME. The time required to determine or to isolate the cause of a system malfunction. It does not include the time required to replace or to repair the units in which the fault occurred.

TRUNCATION. Truncation of a distribution means deletion of portions greater than a certain value and/or less than a certain value. Truncation of a sequential test means termination of the test prior to reaching a decision under the sequential plan.

UNIT. A general term indicating any part or combination of parts.

UNIVERSE. Same as POPULATION.

USE RELIABILITY. The reliability achieved under actual end-use conditions.

USEFUL LIFE. The total operating time between debugging and wearout.

VARIABLE. A quantity or characteristic that is not fixed. A continuous variable may assume any value within a defined range. A discrete variable may assume any one of a number of distinct or seperate values.

VARIABLES (METHOD OF). Measurement of quality by the method of variables consists in measuring and recording the numerical magnitude of a quality characteristic for each of the units in the group under consideration.

VARIABLES TESTING. A test procedure where the items under test are classified according to quantitative rather than qualitative characteristics.

VARIANCE. The variance (about the mean μ as its origin) of a random variate X (and of its distribution) is defined by the expression:

$$\int_{-\infty}^{\infty} (x - \mu)^2 f(x)\, dx$$

when f is the frequency function of x. When x is discrete, then its variance

$$\sum_{\text{all } x} (x - \mu)^2 \Pr(X = x)$$

where the summation is extended over all values which x assumes. Variance is also the square of the standard deviation (σ).

VARIATE. A variable.

WARM-UP TIME. The time measured from the application of power to an operable system to the instant when the system is capable of functioning in its intended fashion.

WEAROUT. Those failures which occur as a result of deterioration process or mechanical wear and whose probability of occurrence increases with time. Wearout failures are those failures that occur generally near the end of life of an item and are usually characterized by chemical or mechanical changes, i.e., those failures which could have been prevented by a replacement policy based on the known wearout characteristics (and thus been prevented by appropriate maintenance). Examples: motor brush wearout.

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